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BULLETIN
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NOVEMBER, 1949

STRUCTURE OF GRAND SALINE SALT DOME, VAN ZANDT COUNTY, TEXAS[1]

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Chicago, Illinois

ABSTRACT

A part of the Grand Saline, Texas, salt dome is exposed in the Morton Salt Company's Kleer Mine. The megascopic structural features of the salt were mapped on all available surfaces, and oriented specimens were examined microscopically. Layers of salt are visible in all tunnels. Near the southeastern border of the dome, they dip steeply southeast and south, assumably parallel with the dome border. Elsewhere, the layers form intricate systems of folds. The axes of all folds plunge nearly vertically, and the limbs are also in steep planes.

The microscopic features of the salt resemble closely those described by Taylor in other salt domes. Anhydrite and halite display a linear alignment. Single crystals of anhydrite, elongate parallel with the crystallographic axis *b*, tend to orient this direction parallel with the nearest axes of folds, that is, nearly perpendicularly. Aggregates of anhydrite, also, are slender lenses and streaks in nearly vertical attitudes. Halite grains show elongation in the same direction, though less noticeably.

The absence of any fractures, faults, cross-cutting salt layers, foreign inclusions, and brine indicate an undisturbed evolution of the deformation structure in a nearly homogeneous, layered salt mass, which resembles closely that produced experimentally by Escher and Kuenen. The movements are analyzed that can give rise to folds with vertical axes and lineation, and the critical physical properties of halite are reviewed.

INTRODUCTION

The interior of a few salt domes in the Texas-Louisiana Coastal Plain is accessible in salt mines. Although the borders, roof zones, and dimensions of North American salt domes have been investigated in the past, detailed studies

[1] Manuscript received, April 16, 1949.

[2] University of Chicago. The investigation was the result of informal discussions that led to the formulation of a project by the research committee of the American Association of Petroleum Geologists. For continued interest, the writer is under obligation to Shepard W. Lowman, who was chairman of that committee. Valuable advice and information were received from Marcus A. Hanna, M. King Hubbert, Paul Weaver, and Roy T. Hazzard. For information on mining data, and many courtesies at the mine, thanks are due James E. Hanes, manager of the Morton Salt Company's Grand Saline plant; J. Y. Bell, mine superintendent at the Kleer Mine; and Earl P. Friedline, assistant plant manager. Travelling expenses were defrayed by the University of Chicago. Critical comments and improvements of the manuscript were offered by Marcus A. Hanna and L. L. Nettleton.

of the salt structure in the cores of domes are as yet lacking. The present paper presents the results of such a study.

LOCATION AND GENERAL FEATURES OF DOME

The Grand Saline salt dome stands about 60 miles east of Dallas, in Van Zandt County, northeastern Texas, about a mile south of the town of Grand Saline. U. S. Highway No. 80 and the Texas and Pacific Railroad pass through the town.

Early stages of exploration and salt operation on the dome have been described by Kennedy (48), Cheney (17), and Powers and Hopkins (68, 69). Salt was originally obtained from shallow wells, but in 1929, the Morton Salt Company decided to open a mine. Under exceptionally difficult conditions, a shaft was sunk (85, 86) to a depth of 750 feet, in the southeastern part of the dome, and production from the mine, called the Kleer Mine, began in January, 1931. An account of the dome to 1934 was given by Hanna (36), and recently magnetic and gravity investigations were made in the mine (66).

The flat-topped dome underlies an approximately circular, shallow depression, $1\frac{1}{4}$ miles across, and partly covered by a salt marsh (Fig. 1). More than 20 wells have reached the top of the salt at depths between 212 and 342 feet. Test wells near the southeastern border of the dome struck salt at 615, 653, and 668 feet, but these greater depths are probably due to downward curvature of the salt surface near the border. Cap rock above the salt averages about 25 feet in thickness, though a minimum of 4 feet, and a maximum of 71 feet are on record.

The dome is surrounded by the Eocene Wilcox formation. Layers of friable sandstone and shale, sloping away from the dome at low angles, are seen in several exposures (Fig. 1). Residue from these overlying rocks, largely yellow sand, with *Gryphaea* and silicified wood can be seen at a dump near the Kleer Mine shaft. It is believed that the entire section from the surface down to the cap rock, is composed of this residue, but actual exposures are lacking.

The slope angle of the dome can be estimated on the west and southeast side. On the west, a deep well (Hallville Oil and Gas Company's Lindsey No. 2), $\frac{1}{5}$ mile west of the dome (Fig. 1), failed to reach salt at the depth of 3,842 feet. If a cross section is drawn through this well, a slope angle of the western dome border of at least 69° is obtained (Fig. 1, section *AB*). The slope angle on the southeast side can be estimated from mine data with a fair degree of accuracy as close to 65°. No other figures are available for other wells are either too shallow, or too far from the dome border to permit close approximation.

Salt is produced from one level only, 700 feet below the surface (359 feet below sea-level). Rooms with approximate dimensions of 60 feet (width) by 85 feet (height), are driven from the shaft toward the north, south, east, and west for several hundred feet. Crosscuts and tunnels of smaller cross section connect adjacent rooms, and during the early years of operation, several air courses were driven between rooms, affording insight into the salt structure in some of the

support pillars. About 20 feet below the floors of most rooms are narrow tunnels along the axes of the rooms. Figure 1 shows by shading the part of the dome accessible through mine workings, and Plate 1 has been drawn from mine plans. The approximate distances are: 700 feet north of the shaft; about 500 feet eastward; nearly 1,100 feet south; and 900 feet, or more, west. This is a very small part of the dome, and as nearly half of the salt is left as support pillars, the structure of even this small area is only known in part. Nevertheless, the exposed surfaces of the salt yield significant information on several problems.

GENERAL FEATURES OF SALT

Blocks of run-of-the-mill are white to light gray in color and are aggregates of halite crystals, with a little anhydrite. Although most of the anhydrite grains are clear and colorless, their presence darkens the salt, due to absorption of light. Salt with probably not more than 15 per cent of anhydrite appears nearly black in reflected light. Clean surfaces show abundant cleavages of halite grains, 2–12 millimeters across, though diameters as large as 25 millimeters (1 inch) are found. The most common sizes in this dome are 5–10 millimeters ($\frac{1}{4}$–$\frac{1}{2}$ inch). Judging from preliminary study of salt specimens from flat salt beds in Kansas, New York, and Michigan, and comparison with salt samples from other salt domes, the writer suspects that halite aggregates from domes are generally finer-grained than those of flat, undeformed beds.

Cleavage surfaces of halite reveal commonly a mosaic, in which contiguous, small areas are inclined at a few degrees to each other. Smoothly curved cleavages were also seen. Here and there, a single halite crystal, much larger than the average, is found, These crystals are saved. Flawless ones are valuable for optical purposes, and bent ones are given away to visitors as souvenirs. In this mine, few flawless large crystals have been recovered, in contrast to some of the Louisiana mines. The largest crystal found during the study of the mine walls measured 6 by 1.5 inches; two others measured 4 by 5, and 3 by 3.5 inches, respectively.

We are indebted to R. C. Vail, general plant manager of the Morton Salt Company, for two recent analyses of Grand Saline salt.[3]

Calcium carbonate	0.010	0.010
Calcium sulphate, anhydrous	0.690	0.571
Calcium sulphate, soluble	0.409	0.470
Sodium sulphate	0.008	0.023
Magnesium chloride	trace	
Insoluble matter	trace	
Sodium chloride (by diff.)	98.883	98.926

Microscopic features.—Twenty-five thin sections were prepared from selected specimens, and for purposes of comparison, three thin sections were examined from the Carey salt mine at Hutchinson, Kansas, which operates a flat Permian salt bed (67, p. 90). Most of the observations by Taylor (87) on the microscopic

[3] Letter to the writer, dated May 28, 1949.

features of Gulf Coast salt were confirmed, and the description is therefore brief.

The salt aggregate is composed of clear, colorless halite grains, entirely free from strain birefringence. A few anhydrite grains are seen in every thin section, and where anhydrite is more abundant, both halite and anhydrite are smaller-grained. Cubical, rectangular, or more irregular "negative crystals" appear in many halite grains. Some contain a bubble, others do not, and may be filled either with brine, or gas. Most of these hollows are minute, about 0.01 millimeter or less in diameter, though tubular blebs may reach a length of 0.1 millimeter. Most of these minute interpositions are concentrated on straight, or slightly curved planes. In several places, these planes coincide with, or lie close to, the dodecahedron planes of the enclosing halite crystal (Figs. 2, 3), though they may also be found along cleavage planes, and even without apparent relationship to crystallographically prominent planes of the host mineral. A careful investigation of the exact orientation of these surfaces with regard to the host mineral, and their distribution in the salt dome, may be interesting and rewarding, and the results may advance our knowledge of the deformation mechanism of the salt. The fact that some of the planes coincide with the dodecahedron planes of halite, which constitute the principal planes of translation under stress, suggests that the distribution of gas, brine, or both, has been influenced to some extent by slip of halite crystals.

Anhydrite forms euhedral and subhedral grains, for the most part free from foreign inclusions. An average grain size is about 0.1 millimeter. Grains of 0.2 millimeter are noted as somewhat oversize. Taylor's observation (87, p. 37) that anhydrite grains are smaller in impure salt, was confirmed at Grand Saline. It should be emphasized, however, that randomly oriented sections can give a false impression, as explained later.

A fair proportion of anhydrite grains are elongate parallel with the crystallographic axis, *b*. This was checked in every thin section. The crystals are terminated by the three pinacoids, and inspection with the universal stage shows that they are commonly grooved, and that the crystals taper toward the ends by several steps, which are alternations of the pinacoids. Cleavage is commonly parallel with the three pinacoids, but cracks parallel with the basal pinacoid, (001), are more perfect than those parallel with the other two. The crystals appear to be fresh. Alteration to gypsum was noted in one place only, and in other sections, also, gypsum was much rarer than the chemical analyses of the salt suggest.

Two individuals of a carbonate, probably dolomite, were seen, and apart from dark dust inclusions in both anhydrite and halite, no other minerals were noted.

STRUCTURE OF SALT

LAYERING

The salt of the Grand Saline dome, in common with other Gulf Coast domes, exhibits a layered structure. As one walks along any room, he sees on all vertical

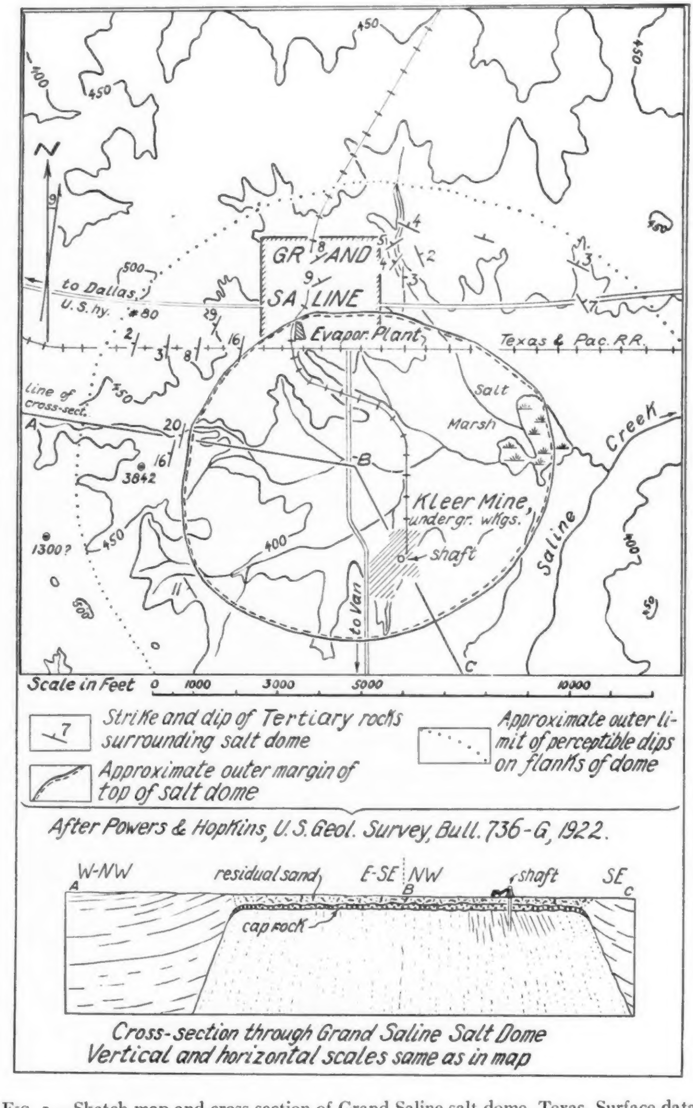


FIG. 1.—Sketch map and cross section of Grand Saline salt dome, Texas. Surface data from Powers and Hopkins (*U. S. Geological Survey*).

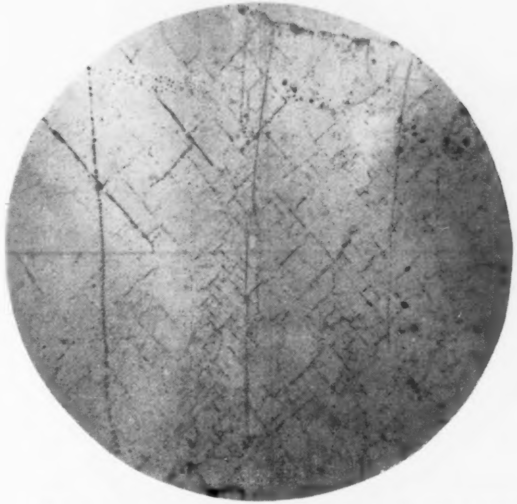


FIG. 2.—Photomicrograph, showing cleavage, and 3 rows of "negative crystals" of brine or gas, parallel with trace of dodecahedron planes in halite (front to back in picture). Location K 3 in mine. Diameter, 1.8 millimeters.

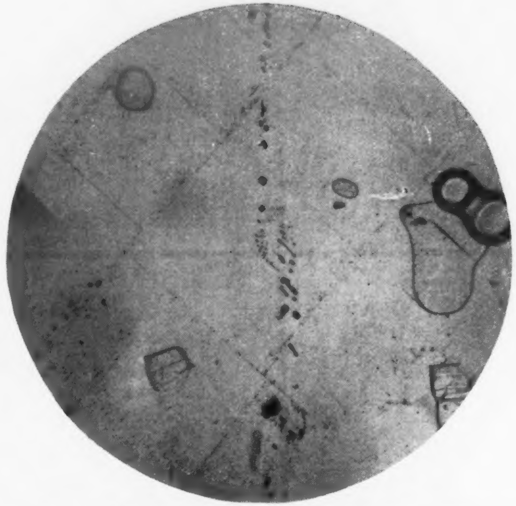


FIG. 3.—Photomicrograph, showing cleavage, and row of "negative crystals" parallel with dodecahedron direction of halite crystal, although each tubule is elongate parallel with directions of cube. Location I 10 in mine. Diameter, 1.8 millimeters.

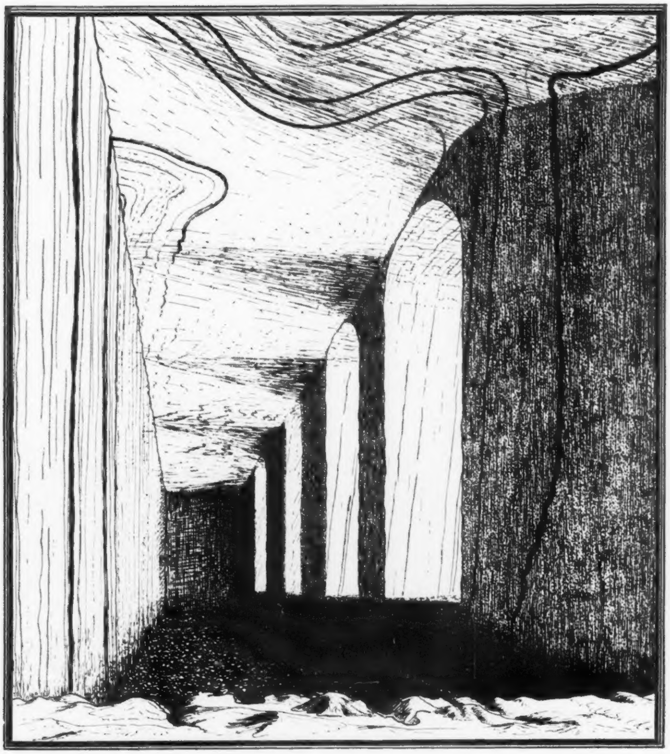


FIG. 4.—Looking westward at location J 9, Kleer Mine. Room is nearly 100 feet high, 60 feet wide, and more than 700 feet long. In ceiling, foreground, several exceptionally dark layers. Apices of folds with diverging limbs in middle and far distance. Between them, relatively massive, pure salt. Note nearly vertical dip of layers on vertical walls.

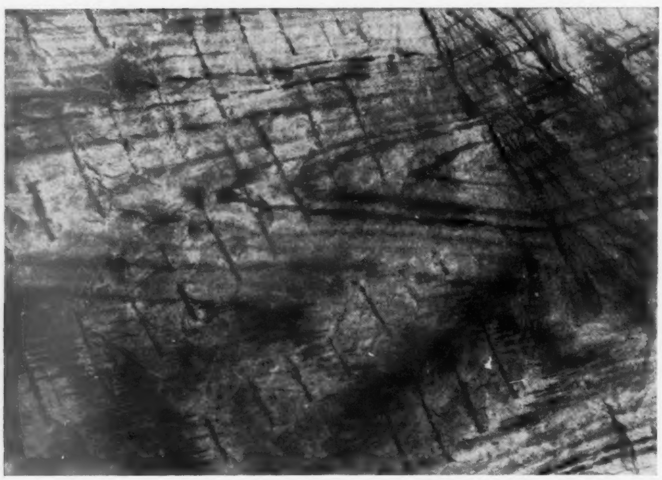


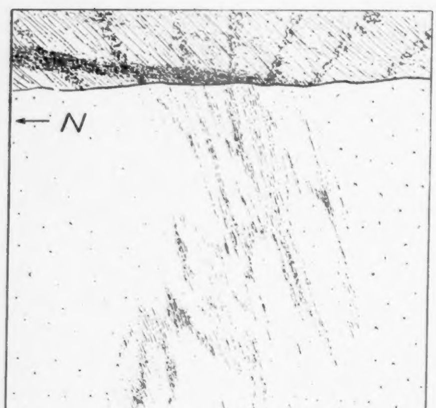
FIG. 5.—Anhydrite layers in ceiling, about 80 feet above camera, at location L 5. Camera is tilted nearly vertically up. Curvature of dark layers, along axial planes of folds, is disturbed by innumerable slip planes, parallel with axial planes of folds, causing small-scale oscillations of traces of beds, but failing to rupture them. Lower right-hand part of picture is vertical wall, displaying vertical beds as parallel streaks.

Fig. 6.—Isoclinal salt folds with shear folds. Ceiling, at location L 4, Kleer Mine. View southward at tilt angle of about 70°. Ceiling is 90–140 feet from camera. Note absence of shear folds in distant folds. Part of vertical west wall shows in lower right-hand corner.

Fig. 7.—Sixty-two shear folds in apical zone of salt fold, at location J 10, Kleer Mine. Ceiling, about 12 feet above camera. More than 100 shear folds were counted in entire apex of this fold. Note absence of shear folds in dark anhydrite layer at top border.

FIG. 8.—Shear folds deforming apical part of anhydrite layer, at location J 10, Kleer Mine. Ceiling of adit tunnel.

FIG. 9.—Anhydrite pencils in nearly vertical position, west wall of tunnel, location J 9, Kleer Mine. Streaks are rendered conspicuous by salt efflorescences. Thick, nearly horizontal white bands are salt dust masses along drill holes. Horizontal bar of ruler is 1 foot.



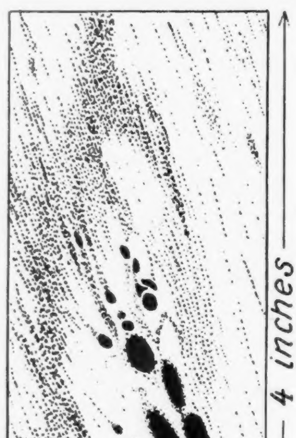
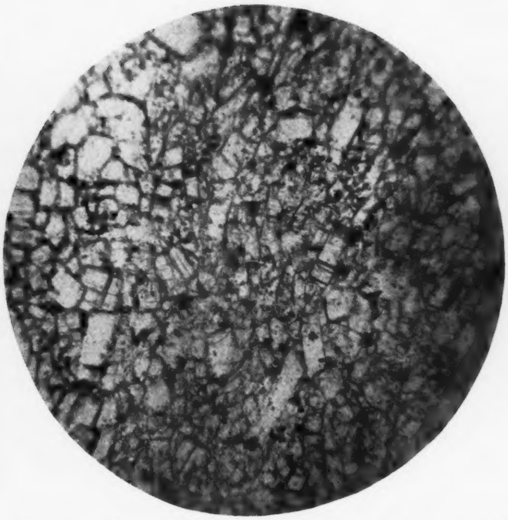
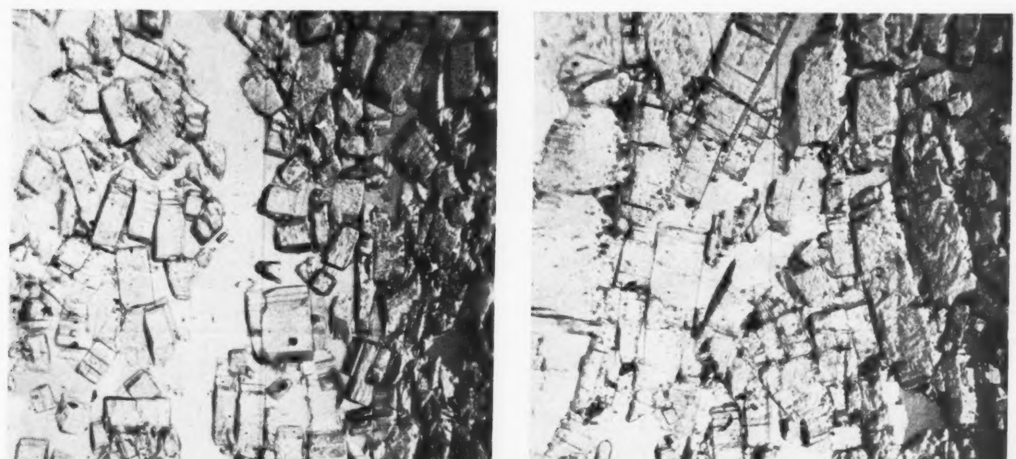


FIG. 11.—Detail view of Figure 10, showing several dark, ellipsoidal halite crystals, enclosed by anhydrite streaks, and elongate parallel with them.

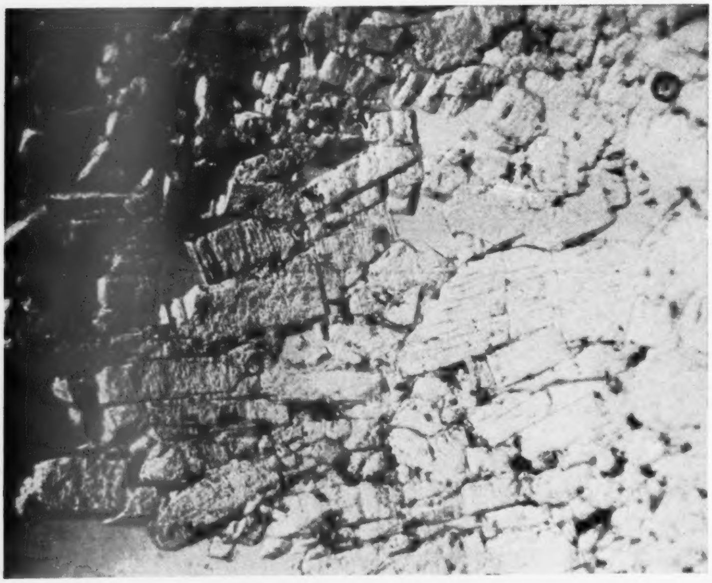
FIG. 10.—Lineation of anhydrite, plunging 72° SE., on east wall of conveyor-belt tunnel, location J 9. Dark anhydrite layer shows in ceiling, striking nearly parallel with wall. Its intersection with tunnel wall is broken into numerous parallel, steeply plunging anhydrite streaks. Here and there spherical or ellipsoidal halite crystals are intermixed with streaks. Compare Figure 11.



Figs. 12 and 13.—Photomicrograph of two vertical anhydrite layers, near location M 8, as seen on horizontal surfaces. Strike of layer is from front to back. Cross sections of prisms are small. Diameter of each picture, 1.8 millimeters.



Figs. 14 and 15.—Photomicrographs of anhydrite layers as seen on vertical surfaces, across strike of layers. Prisms show upward elongation, parallel with strike of beds. White areas between anhydrite crystals are halite. Each picture is 2.5×1.9 millimeters. Fig. 14 at loc. M 8, Fig. 15 at loc. K 3.



FIGS. 16 and 17.—Photomicrographs of anhydrite layers as seen on vertical surface, parallel with layers. Linear elongation of prisms upward (top of pictures) is recognizable, though less pronounced than in views at right angle to this (Figs. 14 and 15). White areas are halite. Each picture is 2.5×1.9 millimeters. Fig. 16 at loc. M 8, Fig. 17 at loc. K 3.

walls a monotonous succession of white and gray stripes in nearly vertical attitude. In several sections of the mine (Pl. 1, locations P 12, M 11–13, L 10, GF 11), hundreds of layers, an inch to several feet thick, form larger groups. Elsewhere individual layers are fewer but considerably thicker, and there are many zones in which layers are difficult to see, and for distances of scores of feet no color variations are noticeable. There is no obvious relation between thickness and darkness of salt layers, although in the Kleer Mine the few very dark layers (Pl. 1, KJ 7–8, J 2; Fig. 4) are less than 5 inches thick.

Boundaries of layers, sharp from the distance, are gradational in specimens and thin sections. Thin salt layers, exposed over sufficiently large surfaces, reveal lenticular forms so that a layer may fade out at a certain height, may continue some distance above or below, or other layers, not visibly connected with it, may occupy closely adjoining positions. The smallest bodies of dark salt are lenticular or irregularly shaped spots and patches in white salt, and where few single anhydrite crystals are uniformly disseminated through halite aggregates, the salt appears compact. Colors other than white and gray were not seen in the dome, although the salt in a few thin sections displays yellow stains along halite cleavages.

FOLDS

General features.—In contrast to the monotonous sequence of parallel layers of salt on vertical walls, the ceilings of rooms and tunnels exhibit an impressive array of folds. Few structural features express the remarkable evolution of a salt dome through deformation as tellingly as the wonderful sweep and beauty of single beds, or swarms of salt layers, trending in broad, smooth curves across the spacious ceilings of large, electrically lighted rooms, forming here a large isoclinal fold, there grouped in numerous smaller flexures that reconcile diverging trends of larger folds. Zones of nearly pure salt with few folds may abruptly be followed by much darker layers with innumerable folds of all sizes and degrees of compression, to be relieved by seemingly straight layers, in which only a powerful floodlight will detect the last remnants of tightly appressed folds. Though peculiar in many respects, the arrangement of salt folds resembles the kinds of flowage folds encountered in many metamorphosed limestones (3; 5, pp. 717–23; 13, pp. 142–54; 28, pp. 55–68; 55; 63; 64).

Distribution, dimensions, orientation.—The southernmost rooms of the mine (A–C 2–7, Pl. 1) are within a few hundred feet of the southeastern border of the dome. It is probably significant that only in this section of the mine are folds almost lacking. The salt here displays straight layers, striking east and west and dipping about 65° southward. In the easternmost of these rooms, the strike veers northeast, but outward dip of 65°–70° is maintained. It is most probable that this angle is parallel with the slope of the southeastern dome border, and it has been so drawn on cross section *BC* of Figure 1.

Apart from these southernmost exposures, the salt in all rooms displays

folds, the mapping of which was the chief purpose of this study; Plate 1 embodies the principal results.

Salt folds vary greatly in size. Some are small, insignificant features, involving only a few, or one single layer. Wave lengths of small contortions are a few inches at most, but where larger groups of layers are involved, wave lengths may increase to more than 100 feet. There are gently curved, open folds as well as tightly compressed, isoclinal folds. The innumerable folds which vary the orientation of their limbs in a bewildering manner, have one element in common: all their axes are parallel, in nearly vertical attitudes. Thus, the fold structure of the salt dome belongs to the relatively rare types of crustal deformation where a vertical element overshadows all other directions of strain. If there were axes that plunge more gently, say, at less than 70°, they would surely have been noticed by the appropriate pattern of diverging and converging limbs on the vertical walls. Not a single cross section of a fold was observed on vertical surfaces. Even those rare instances where adjoining layers do converge slightly, because of oblique intersection of room wall and fold axis, are difficult to detect for the angle of divergence is so small that one must suspect that slight variations in thickness of layers may cause the pattern.

Axial planes of most folds are straight, but those of larger folds may curve. Adjacent folds may or may not display parallel orientation of axial planes. The longest fold extends from near the northern termination of the rooms (Q 7, Pl. 1) in a south-southeasterly, southerly, and southwesterly direction until, about 700 feet from its start, it is lost, near K 5, in a cluster of isoclinal folds. The arcuate axial plane is, in plan, convex toward the east, and this orientation and shape may very well have been brought about and controlled by the probably similar curvature of the eastern border of the dome.

The true length of many folds is difficult to ascertain for support pillars interfere with exposures in individual rooms, and the directions of few folds happen to coincide with those of larger rooms. There are apparently no key beds in this mine that could be followed continuously across all the rooms. This is shown by the very dark layer at J 8 (Fig. 4). It can be followed northwestward across one room, to L7; but at K 6, where it should reappear on the west side of a support wall, it can not be identified. Likewise, its southeastern continuation can not be followed beyond J 9. Although a tunnel crosses the salt only 50 feet south, it was impossible to identify the layer in its ceiling. Similarly, a thick dark layer, at J 2, was followed northeastward about 200 feet, to K 4, but because of several interfering folds at that location it is uncertain whether the dark layer that traverses the next room east (K 4–5), is identical with it. In any case, this latter dark layer can not be recognized in the next room east.

Closure.—At five places (D 2, DE 4, F 1–2, G 14, O 11), closure of salt layers was seen. Possibly there is also closure at H 2 and F 3. One, two, rarely more than four recognizable separate layers participate in closed ellipses in the ceilings which, as seen in Plate 1, are all small. As the mine operates one level only,

nothing is known about the steepness of the flanks of these folds although, in view of the dip angles of adjacent layers, they must be very steep; indeed, each of these elliptical cross sections may well represent a nearly pipe-like body with subvertical axis, only a few feet in diameter, but hundreds, perhaps even thousands of feet long. The ellipses at DE 4 and O 11 are moderately compressed, G 14 is much compressed northwest and southeast, and the elliptical closure at D 2 has been bent on the flank of a larger fold, so that its axis trends northeast and southwest in the south part, and west-northwest and east-southeast in the northwest half. The anhydrite layers that belong to it show intricate small-scale shear folds with slightly diverging axial planes.

A peculiar, isolated dark layer in the form of a semicircle, is exposed in the ceiling of a room at H 2. Its north half is concealed so that it remains unknown whether this is a closed fold, or the south crest of a larger, open fold. The dark layer displays several irregular twists and small-scale contortions, and pinches and swells in a few places.

SHEAR FOLDS

Apart from the larger folds, shown on Plate 1, there are literally thousands of smaller folds, superposed on the limbs of the larger folds. In a series of straight beds, shear folds may appear on a single layer only, either along its entire course, as far as it can be examined, or over a short distance only. Contortions of this type may involve a larger group of adjacent layers. The limbs of the shear folds may be isoclinal, or may diverge in directions, causing rows of zigzags, or chevrons. Impressive are tightly appressed folds of this kind along the axial plane of a group of beds at location, L 5 (Figs. 5, 6). Salt layers whose cross sections approach the axial plane zone as smooth curves are abruptly thrown into scores of isoclinal contortions. The limbs of some of these are so thin that it may be impossible to follow individual beds through each back-and-forth curvature where they are exposed in high ceilings. Instead, one has the impression, at first, of a homogeneous thickening of each layer into a plate of dark salt that has a crescentic plan and a nearly vertical axis. Where many adjacent salt layers have undergone such shear folding, the structure of the salt becomes most difficult to unravel. Such a zone is at L 9–10. Remarkable is the abruptness with which myriads of shear folds may disappear, to be followed by straight, uncontorted layers.

The axial planes of these small shear folds are without exception parallel with the axial planes of the folds on which they are found. Followed through the mine, their directions vary over short distances, and nowhere have shearing movements cut through the limbs of folds. Instead, even very thin anhydrite layers can be traced continuously through dozens of shear folds without showing rupture anywhere (Figs. 7, 8).

It seems, therefore, that the shear folds developed in response to the same stresses that governed the directions of compression of the larger folds. Not

only do the axial planes in both groups of folds follow the same direction, but the displacements along the small shear folds are almost everywhere such that the layers were lengthened toward the apices of folds, and relatively narrowed at right angles to this direction. Thus, the considerable thickening of salt layers near the apices of folds may have been caused by a homogéneous movement of all constituent particles, or may have been accomplished, in part, by slip along innumerable parallel planes. The halite-anhydrite aggregate seems to have moved as so ductile a mass, however, that actual ruptures of anhydrite layers were avoided.

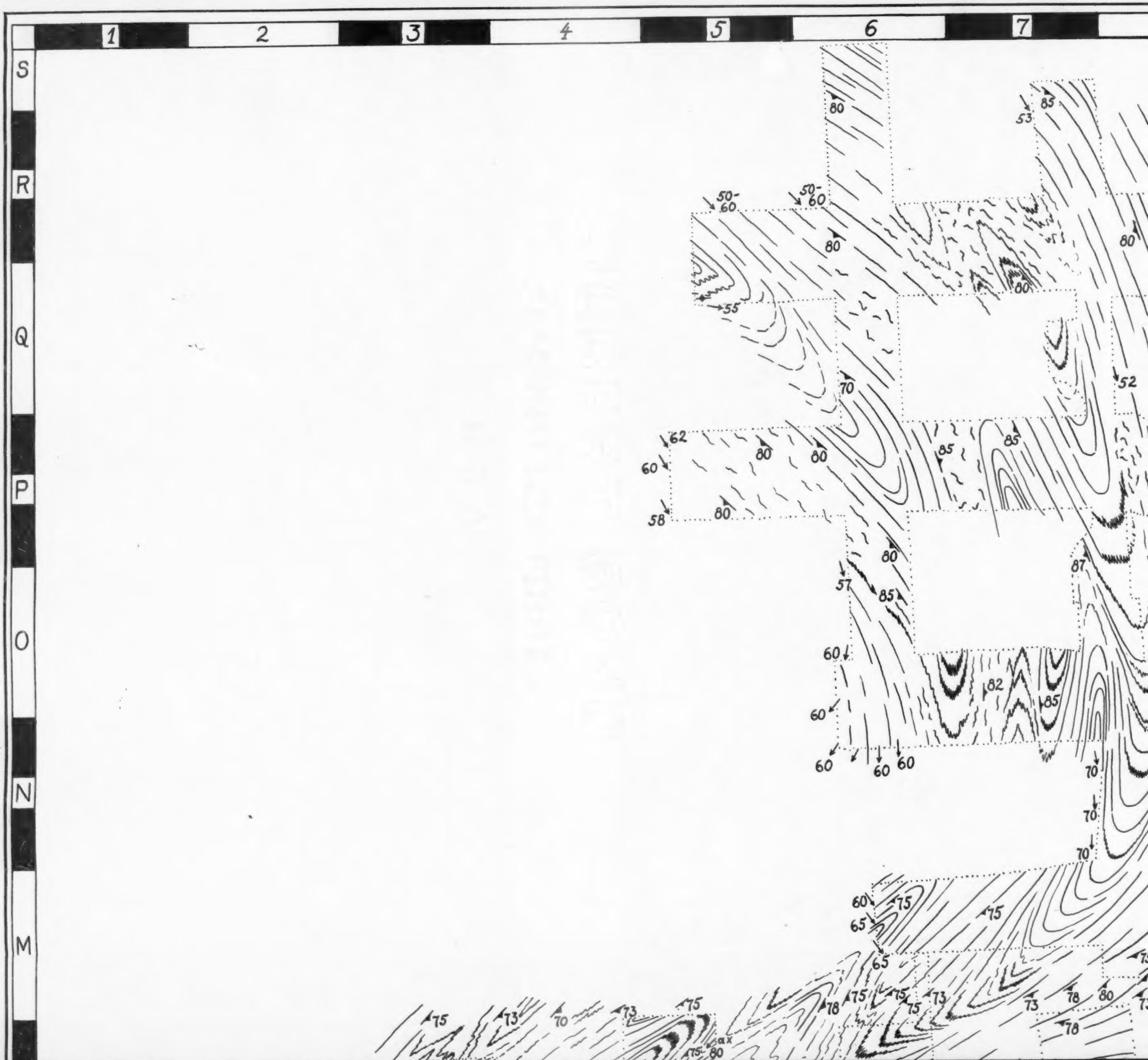
Small-scale isoclinal folds, apparently identical with those here described, are known from German salt upthrusts (37, 38, 81). Hartwig calls them "salt seismograms" (38, p. 197), and apparently believes that they originated through seismic tremors. The writer is unable to understand how tremors should be able to produce in a salt mass thousands of microflexures, oriented parallel with the axial planes of local folds, and nowhere actually rupturing the salt.

LINEATION

A linear alignment of minerals is commonly observed in strongly deformed rocks. It is particularly well developed if lengthening in one direction was appreciably greater than deformation in others. Prismatic particles, embedded in softer material, will then be exposed to rotational moments that rotate their axes into the direction of lengthening. The same mechanism is believed to operate where plastics, composed of large organic chain molecules, are stretched (2). The stretching causes an alignment of the chains in the direction of stretching, with attendant change in the mechanical properties of the plastic. The importance of lineation for the interpretation of rock deformation has recently been discussed by Ernst Cloos (20), who has reviewed the literature on the subject up to 1945. The salt of the Grand Saline dome exhibits a linear alignment of its constituent minerals at so many places in the mine that the belief seems justified that the entire salt body possesses this structure. Depending on whether anhydrite or halite is the dominant mineral on any surface, the appearance of the structure varies somewhat.

Lineation of anhydrite.—A linear arrangement of anhydrite aggregates was first seen by the writer in August, 1946, at the mine of the Carey Salt Company in the Winnfield salt dome, Louisiana. Through the break of a water pipe on a holiday, the mine had been partly flooded, and the rising water etched out as much as a foot of salt on all room and tunnel walls, to a height of about 3 feet. On the smooth, corroded salt walls innumerable pencil- or cigar-shaped masses of anhydrite stood out, pointing nearly straight up. In conversation with M. C. Mann, chemist of the company, the writer learned that this type of anhydrite aggregates was well known to him, and was called "pencil anhydrite." Taylor (87, p. 28) is also familiar with it.

The salt at Grand Saline displays the same linear alignment of anhydrite



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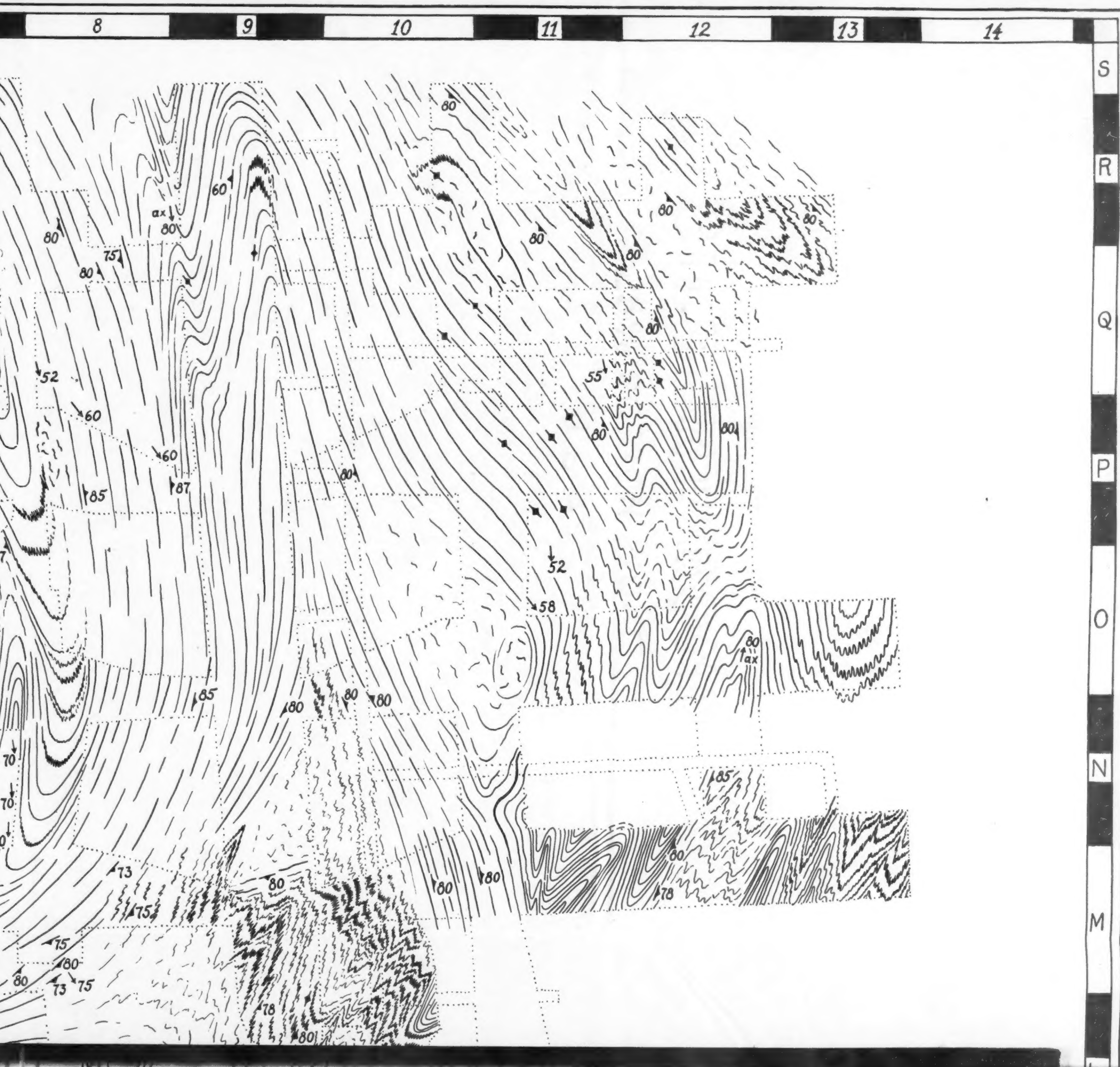
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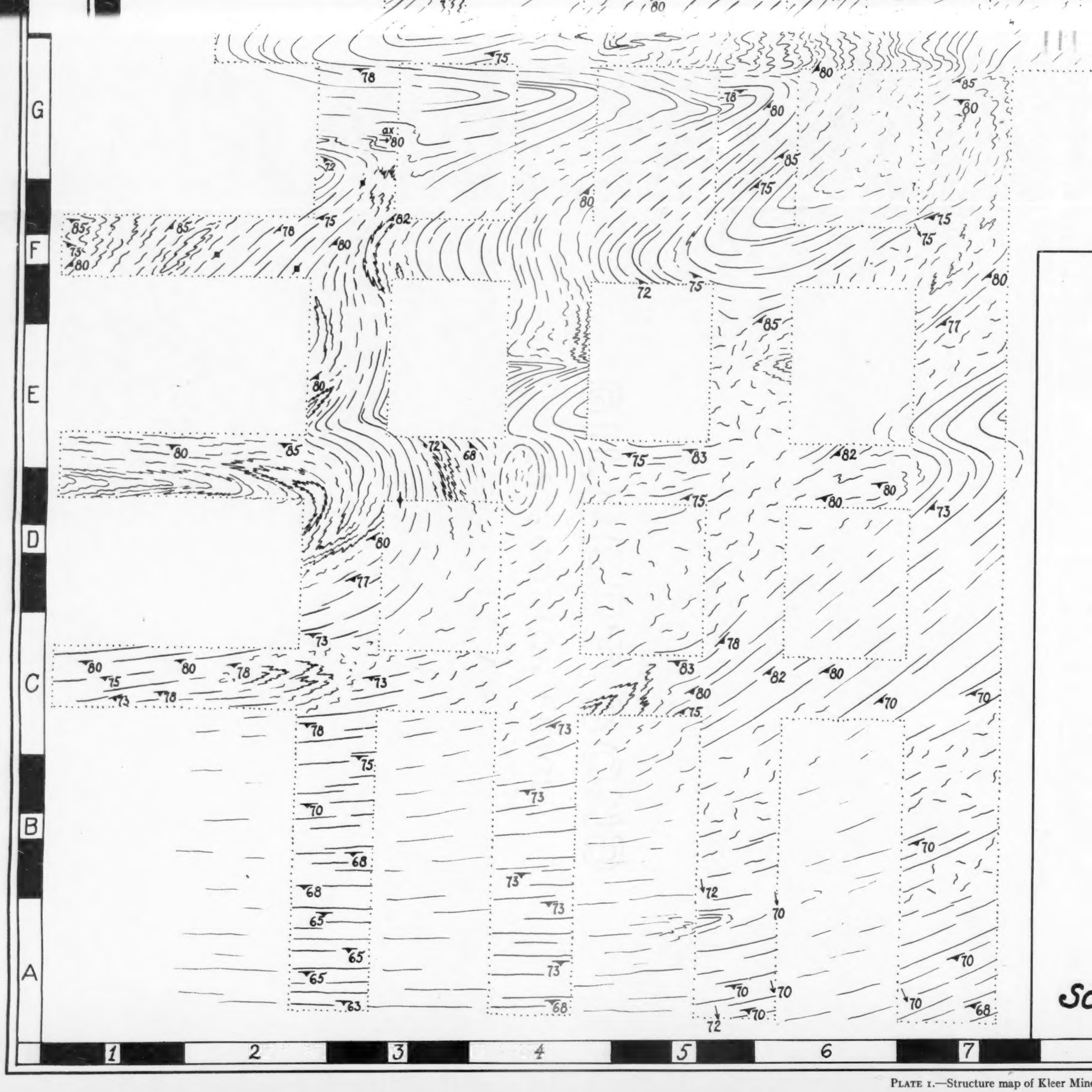
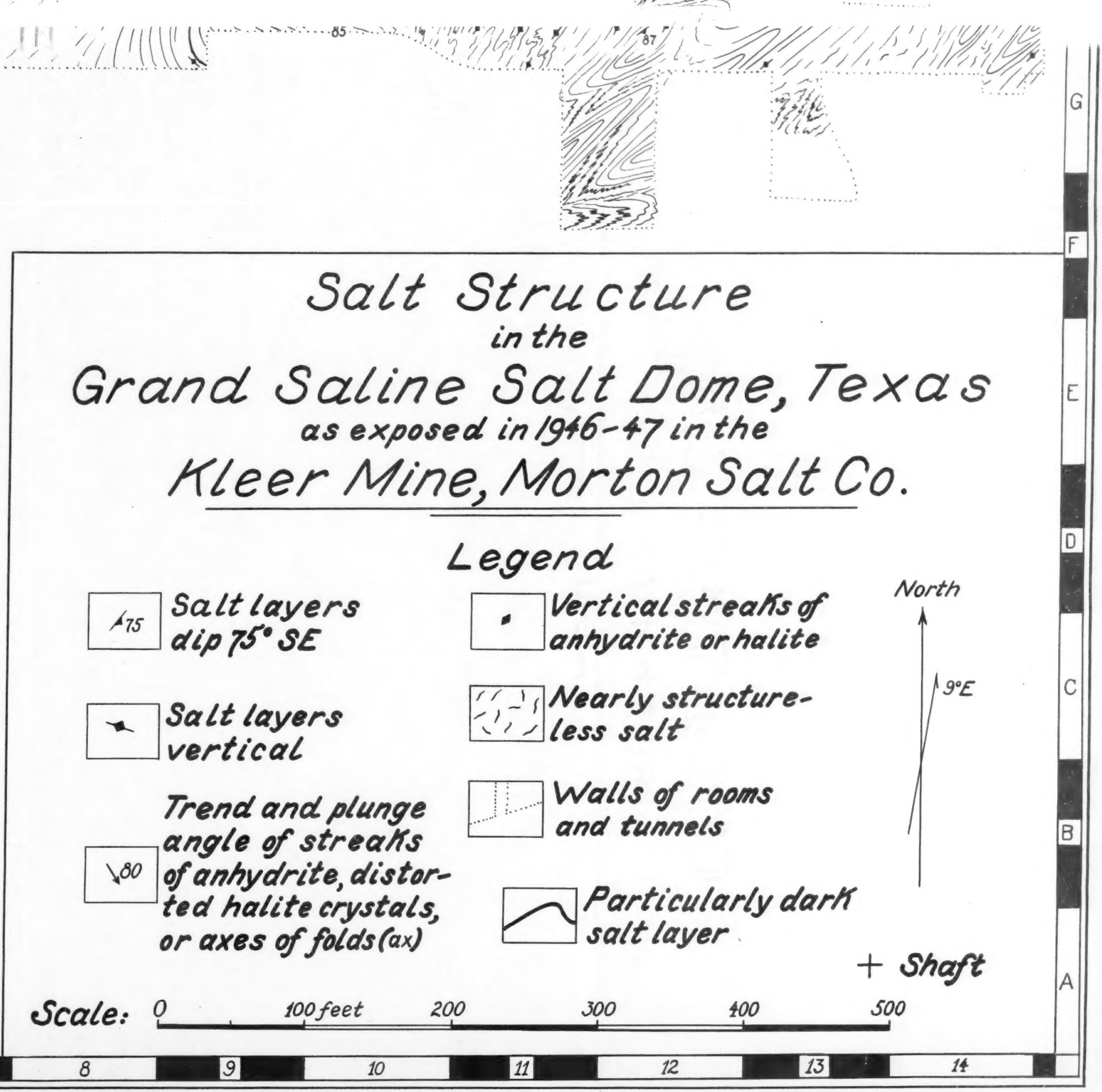


PLATE I.—Structure map of Kleer Min

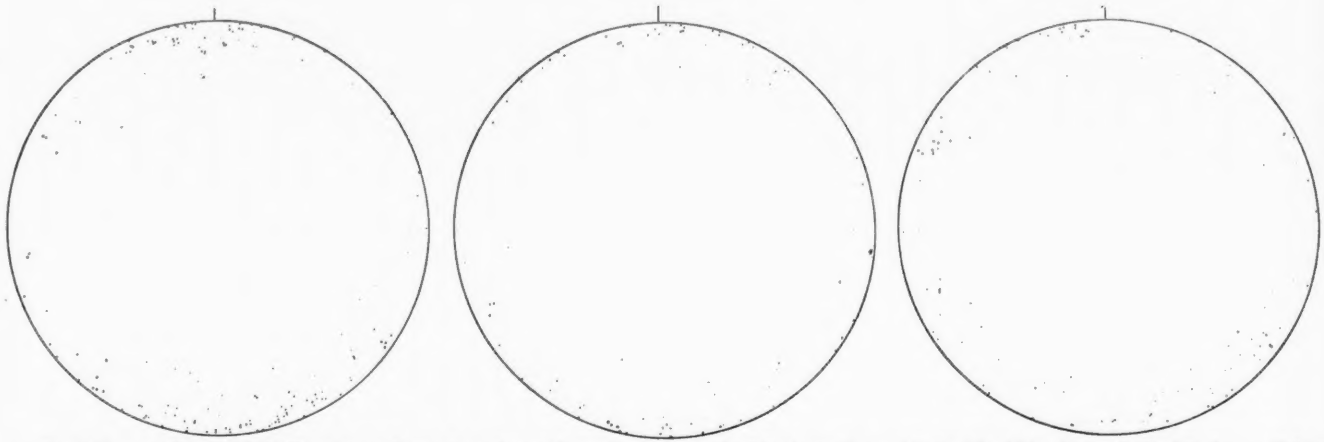


of Kleer Mine, Grand Saline, Texas.

crystals, and as at Winnfield the direction of lengthening nowhere deviates more than about 20° from verticality (Figs. 9–11, Pl. 1). Although the borders of anhydrite pencils are not sharp, the streaks can be viewed if salt blocks containing them are dissolved in water. For a while, the streaks will stand out in relief, and if care is taken that they come to rest on a soft support, parts of the streaks can be preserved. Linear tracts of anhydrite are a few millimeters in diameter, and 2, 3, or more inches long. Outcrops of particularly anhydrite-rich layers are commonly composed of, and accompanied by, large swarms of these streaks, all pointing in the same direction (Fig. 10). Cross sections, obtainable where salt has been freshly blasted, or recesses and drill holes afford horizontal surfaces, are elliptical, with the major axis parallel with the strike of the anhydrite layer. On the walls of old tunnels, anhydrite streaks are fairly easy to see as they become coated with salt efflorescences and dust (Fig. 9), yet they are seen more easily than measured. As the intersection of any anhydrite layer and vertical mine surface produces a nearly vertical line, these intersections of planes can be mistaken for streaks. It is necessary, therefore, to examine such places where anhydrite layers strike as nearly parallel with the mine wall as possible or, where this is impossible, to examine with care the small-scale irregularities in the mine walls, so that only those small surfaces are used where, for a few square feet or even square inches, the two planar elements are nearly parallel. It may also be possible to ascertain the linear shape of the aggregates near corners in the mine, by examining the width of outcrop and vertical length of anhydrite aggregates on the two opposite surfaces; and finally, one can infer the shape in such salt masses that lack layers, yet exhibit anhydrite streaks in upright position on surfaces of different orientations.

Under the microscope, anhydrite pencils are seen to be composed of rows of relatively small crystals, in which perhaps 5–10 per cent lie with their longest dimension parallel with the axis of the pencil. The longer and slenderer a grain is, the more closely is it aligned. As the grains are elongated parallel with the crystallographic axis, *b*, the dimensional order of the crystals entails a corresponding alignment of this crystallographic axis but, in the material examined, no systematic orientation of the crystallographic axes, *a* and *c*, was noted. Figures 12–21 illustrate the grain orientation. Insofar as the crystallographic axis, *b*, is parallel with the axes of salt folds, this agrees with the orientation described by Lamcke (51) and Andreatta (1), and summarized by Fairbairn (32, p. 19). Small grains, which are squares in cross sections, orient a diagonal diameter parallel with the lineation direction. For this reason, the diagrams of *b*-axes of anhydrite grains (Figs. 18–20) do not show sharp maxima in the direction of the lineation, but considerable scattering, and if a model be made of the orientation of the *b*-axes, it would be a double cone, having the lineation direction as its axis, and sides that slope nearly 45°. Essentially the same orientation of anhydrite in German salt is given by J. Leonhardt (52, pp. 101, 102).

Lineation of halite.—Lineation of halite grains is more difficult to see than



FIGS. 18, 19, and 20.—Fabric diagrams to show orientation of elongate prisms of anhydrite (crystallographic *b*-axis) within planes of anhydrite layers. Points form incomplete girdles within plane of layer. Deviations from verticality due, in part, to tendency of short prisms to orient their diagonal upward as this is longest body axis. All sections cut vertically, parallel with layers. Black line at top of periphery of circle points up.

Fig. 18: 193 grains, loc. M 8.
Fig. 19: 115 grains, loc. J 9.
Fig. 20: 142 grains, loc. L 3.

that of anhydrite, but if clean vertical walls are inspected with a strong flashlight, the surfaces of reflecting halite cleavages show rectangular or elliptical shapes. With some experience, the direction of elongation can be seen where as few as 2–5 per cent of the halite crystals exhibit unequal diameters. It was first thought that the phenomenon was caused by accidental fractures developed during the blasting, but as more and more observations were gathered, it became obvious that halite grains are commonly of distorted shape, and that the longest

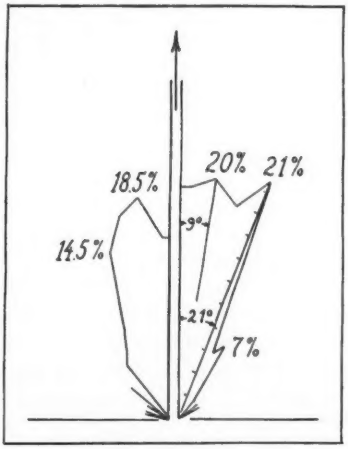


FIG. 21.—Alignment diagram of elongate anhydrite grains in thin sections from locations J 9 (left, 203 grains), and M 8 (right, 100 grains). Left section cut at right angles to megascopic layering, right section parallel with layering. Arrow, at top of diagram, points up in mine. Number of grains plotted as lengths of radii; scale of 2 per cent lengths is ticked on radius on right diagram. Figures in diagram, e.g., "20%" mean that 20 per cent of measured grains of that section deviate 9° from verticality. This type of diagram reliably records angular deviation of grain elongation from verticality in one plane, but does not give tilt of crystallographic axis out of plane of thin section. This is obtained by slower method of determination with universal stage (Figs. 18–20).

dimensions of these grains, like the anhydrite prisms, point in nearly vertical directions.

As halite crystals are isotropic, and too large for ordinary thin-section work, it is necessary to measure them on large, clean surfaces, as well as in oriented blocks. Figure 22 gives measurements of 700 crystals, obtained from various locations in the mine. Vertical surfaces were flashed from various sides in order to locate as many grains as possible. The two principal diameters of each grain were measured, and the measured grain received a black dot lest it be measured again. Oriented blocks were measured in the same way. The figures have qualitative value only for the direction of lengthening of very small grains could not be measured. On the other hand, the small (7.1) percentage of grains elongate horizontally is probably significant.

That the inequidimensional cleavage surfaces are due to oriented distorted shapes of the crystals can be checked at places where the lineation direction deviates as much as possible from verticality. At such places, if edges of pillars and rooms are selected, and grains on both surfaces are compared, the diameters are

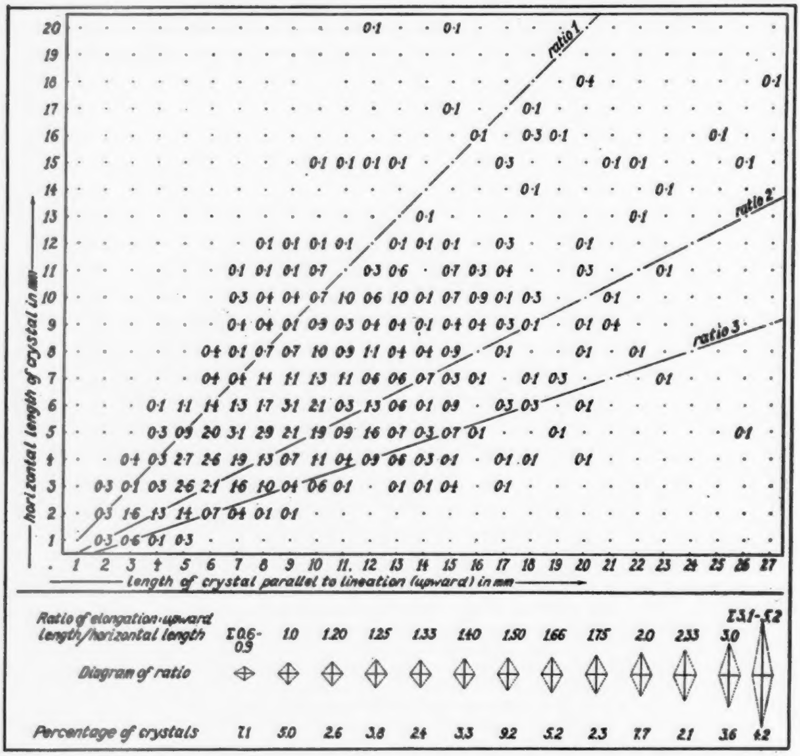


FIG. 22.—Chart to illustrate degree of upward elongation of 700 distorted halite grains, from various locations in Kleer Mine. Key for upper diagram: "0.3" in lower left-hand corner means that 0.3 per cent of 700 (=2) grains measured 2 millimeters up, and 1 millimeter horizontally. In lower diagram, data of upper diagram are combined as ratio figures, and cross sections illustrate corresponding shapes of idealized grains. Bottom row of figures gives percentage of grains that belong to each ratio.

longer on that surface that embraces a vertical plane passed through the lineation or is closest to that plane.

Inspection of the structure map shows that nearly the entire salt mass is composed of visibly elongate aggregates of anhydrite and halite, in nearly perpendicular orientation, and that this direction is parallel with that of the axes of the folds. There is, perhaps, one exception to this: at O–R 5–8, the direction of length-

ening of halite crystals seems to plunge at lower angles (50°–65°) than the orientation of axes and limbs of near-by folds. The reason for the discrepancy is obscure. Subsequent studies in other salt domes may show whether such discrepancies are more common than the writer at present assumes.

COMPACT SALT

On Plate 1, a cross-hatch pattern shows the distribution of compact salt, in which layers are restricted to few, very light "shadows," lenses, patches, or may be altogether lacking. As nearly structureless salt is somewhat purer than ordinary layered salt, its distribution within the salt dome is of considerable commercial importance. If preliminary estimates are correct, compact salt is slightly coarser than layered salt, and it is perhaps significant that during our visit, all large single crystals were found in compact salt masses. The borders of compact salt masses are elusive; near-by anhydrite layers fade out gradually, or the continuity of layers is replaced by rows of gray lenses, each with blurred, irregular outlines.

A number of these masses appear in positions where the surrounding groups of layers make sharp bends (H 10, K 10, J 10–11), or where one group is confronted by others of contrasting strike (HI 4, I 6–8, J 12, G 6). Still others (DE 4, O 11) fill the cores of closures, or have irregular plans though their lateral borders seem to be smooth, nearly vertical zones of gradation. Lineation in compact salt is obscure, but was seen at a few places.

Nowhere has a mass of structureless salt been seen that would cross, or cut off, adjacent layers, after the manner of a dike, or pipe. It would be interesting to know whether compact salt differs in moisture content from layered salt. J. Y. Bell informed the writer that run-of-the-mill salt contains less than 1 per cent moisture, but whether there is a difference among different kinds of salt could not be learned. To obtain uncontaminated blocks of salt, immediately after blasting, is most difficult, and the writer lacked facilities for such sampling.

NEGATIVE FEATURES

For the understanding of the development of this salt dome, the following negative features are significant. 1. Not a single fracture is exposed in the mine. 2. Nowhere is salt displaced by a fault. 3. Salt layers are nowhere crossed by others, and there are no unconformable contacts between layers. Where groups of salt layers approach each other with contrasting strikes, a zone of compact salt intervenes. 4. No brine or gas is encountered, except as microscopic interpositions in halite crystals. 5. No inclusions of foreign rocks have been found in this mine. 6. Although no systematic search has been made for minerals other than halite and anhydrite, it is believed that additional minerals, such as dolomite, or sulphides, are very rare.

Compared with the widespread evidences of rupturing, faulting, and thrusting, or large-scale slipping as inferred from stratigraphic anomalies in European

salt upthrusts, the structure of this salt dome is characterized throughout by the uniformity and, in a way, simplicity of its deformational structures. An attempt to explain its structure, therefore, is essentially concerned with an interpretation of the folds with nearly vertical axes, and the linear alignment of the aggregate in the same direction, and it is necessary to inquire to what extent the visible large- and small-scale deformation can be explained by the known physical properties of salt.

INTERPRETATION OF OBSERVATIONS

As only a small part of the dome interior is exposed, and the base of the dome has not been reached by a well, it is necessary to make certain assumptions in order to interpret the structure of the dome. An exhaustive digest of the large literature of Coastal Plain geology, as well as that of the physical properties of halite and other halogen salts, could not be included here as it was deemed desirable that the results of the Grand Saline study be published fairly promptly. As the writer expects to continue his studies, he hopes to add corrections in the future, and would in turn be grateful if serious omissions and errors be brought to his attention.

DIMENSIONS AND VOLUME OF DOME

The dome may be considered to be a truncated cone, having a circular top surface with a radius of 0.63 mile (68, p. 222), and borders that slope about 70° outward on all sides. The source bed of the dome is not exactly known, but recent compilation of subsurface data in northern Louisiana and northeastern Texas by the Shreveport Geological Society (39, pp. 488–90) justifies the assumption that the Grand Saline dome is underlain by the pre-Cretaceous Louann salt, which has been drilled southwest of the dome, in Limestone County, Texas, at a depth of 8,995 feet (39, Table V, p. 490). In conversation with oil geologists, the writer learned that depths between 15,000 and 20,000 feet are being considered for the mother layer. About the same figure has been suggested by Nettleton (60, p. 1177, footnote 6).

If the salt dome is assumed to be 3 miles high (15,840 feet), and has slopes of 70°, it would have a bottom radius

$$0.63+(3\cdot\tan 20^\circ)=1.72 \text{ miles.}$$

Applying the formula for the volume of a frustum of a cone,

$$\frac{\pi}{3}\cdot h\cdot [R^2+Rr+r^2],$$

in which h is the height (3 miles), R the radius of the base (1.72 miles), and r the radius of the top surface (0.63 mile), we obtain for the volume of the salt dome

$$1.047\cdot 3\cdot 4.43=13.92 \text{ cubic miles.}$$

If Peters and Dugan's figures are taken (66, Fig. 13), the shape of the dome is nearly that of a vertical column, not quite 3 miles high, and with an estimated radius of 2,000–4,000 feet. Calculated from this form, it would have a volume between 1.36 and 5.26 cubic miles.

Before the dome rose, this amount of salt is assumed to have been a part of a flat layer, for which Barton (9, pp. 42–43) has calculated a probable thickness of 700 feet. The latest compilation of thickness of the Louann salt, as given by Hazzard, Spooner, and Blanpied (39) and Nettleton as reported by Willis (89, p. 1249) shows variations in either direction but for purposes of obtaining merely the order of magnitude, the figure of 700 feet seems satisfactory. A cylinder, 700 feet high, with a volume, $\pi \cdot r^2 \cdot h$, corresponding with that of the Grand Saline dome, would have a radius of approximately 6 miles. If the figures given by Peters and Dugan are applied, the salt would have migrated laterally about 1,000 feet to 3.5 miles. Salt from that distance would have to move into, and toward, the dome before a peripheral depression put an end to the centripetal motion—if a depression developed (27, p. 541). As the dome is truncated and covered by cap rock, however, it is possible that a larger amount of salt has moved into and through the dome, but how much larger is unknown.

MOVEMENT OF SALT

LARGE-SCALE MOTION

The most significant large-scale structure of the salt in the Kleer Mine, as stated before, is the folding with nearly vertical axes. It is fortunate that the development of such folds in a plug-like mass is easily understood, and has been tested experimentally with great success by Escher and Kuenen (30). Flat layers of china clay and paraffine that were extruded into a chimney, developed numerous folds with vertical axes. Folds were suppressed, however, if the layers had the same rheological properties, for instance, paraffine layers without china clay layers between (30, p. 170). The writer is indebted to James Bailey, vice-president and director of research, Plax Corporation, Hartford, Connecticut, for making similar extrusion experiments with a variety of materials. Layers of putty, separated by sheets of tissue paper, produce folds, whereas layers of plastic, having practically uniform flow properties, are drawn up into a slender, cylindrical, dome, but fail to form folds. These experiments are being continued, and at a later time will be reported.

Escher and Kuenen have discussed the reasons for the vertical axes of the folds. While the direction of principal propagation of the whole material is centripetally inward and upward, the converging motion of all particles generates peripheral, tangential stresses. Their varying directions would be represented by horizontal lines, drawn on the surface of the cone. As these stresses act parallel with the layers, they constitute shearing stresses. If the material chosen is homogeneous, there is a continuous gradation of the rate of yielding from one small

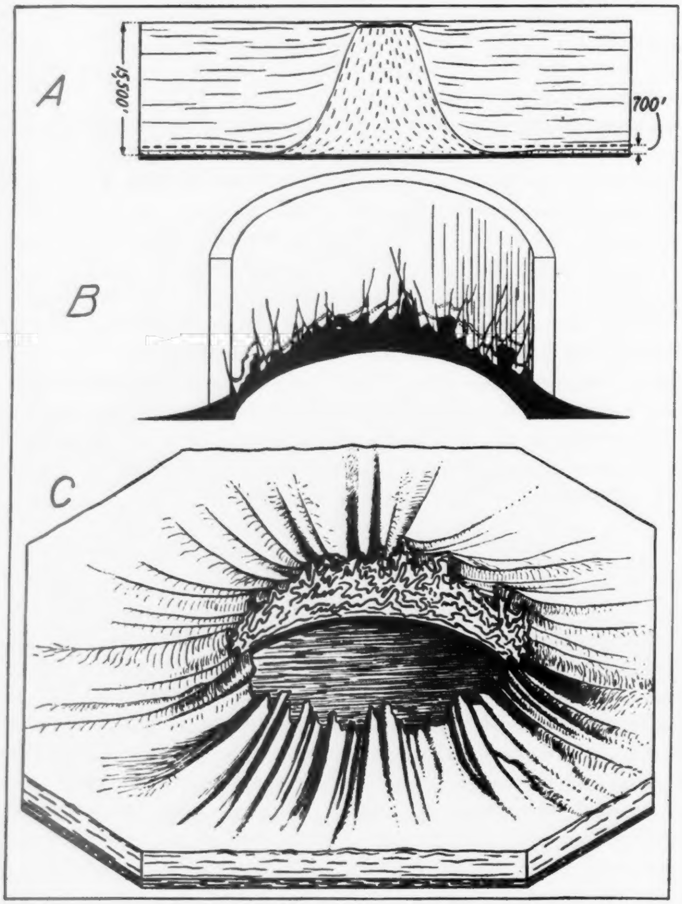


FIG. 23.—Diagrams to illustrate probable dimensions and structural features of Grand Saline salt dome.

A.—Cross section of salt dome, to scale, rising about 3 miles above hypothetical mother layer (dotted, above black floor of mother layer). Dash line: top of hypothetical 700-foot mother salt layer, prior to flow of salt into dome. Present thickness appreciably less, perhaps zero if peripheral sink has squeezed it out. Black area, on top of dome: cap rock. Blank area above cap rock: residue of Eocene sediments. Dashes on sides of dome: Eocene, and earlier sediments.

B.—Surface of hypothetical cylinder truncating salt dome near base, to show possible accommodation of rising dome by faulting in sedimentary cover. Double-dash line: Hypothetical key bed to indicate assumed slip component on faults.

C.—Structure of salt layers, near base of salt dome, on surface of hypothetical vertical cylinder. Flat surface, surrounding dome, signifies top of salt bed, with cover of sedimentary rocks increasing outward. Numerous folds, in radial directions, rise toward axis of dome. Each anticline is assumed to be underlain by anticlinal salt layers, leading to complex structure inside salt dome, as shown on vertical surface of cylinder. Rear part of this surface is identical with corresponding surface of diagram B.

area to another, but if the mobility[4] of adjacent layers varies abruptly, the rates of yielding will also vary abruptly so that one layer, or one group of layers, must slip over or under adjacent layers. If the differences in mechanical properties are extreme, fractures and faults may occur, but folds will suffice if the strongest layers possess enough ductility to bend without fracture.

Thus there originate around the periphery, at the base of the dome, numerous folds whose axes trend radially, and plunge outward from the dome in all directions (Fig. 23). A simple and familiar way of reproducing this fold pattern is to raise several horizontal sheets through a horizontal ring. If the sheets differ in stiffness, the shearing of one sheet over another can be directly observed.

That converging lines of movement are apt to produce folds parallel with the direction of forward propagation, was recognized by Ernst Cloos (20, p. 28) in connection with his studies in lineation and folds in thrust sheets, and the mechanism of acceleration flow of J. H. Mackin (54, pp. 27–32) is essentially identical with it, except that Mackin was concerned with the development of lineation, rather than fold axes, parallel with the direction of propagation.

It seems impossible to predict just where individual folds will start to form, and how many layers will fold conformably in a thick sequence or where folds with different wave lengths will begin, if the contrasts in mechanical properties are not extreme. In the salt-layer sequence, at any rate, the behavior of any layer seems to have been governed by the percentage of admixed brittle anhydrite grains. Other important factors are, assumably, the amount of overburden, the degree of compaction, and manner of yielding of the roof in each particular area, as well as variations in friction-coupling among the salt layers. The roof of a rising salt dome is not a smooth, trumpet-like surface but, more probably, a multitude of irregular salients, recesses, and sags, regardless of whether the roof yields by bending, or complex faulting. Each irregularity of the roof is likely to give rise to fields of greater or lesser shearing stresses, and thus should generate velocity differences between individual groups of salt layers.

As each mass of salt approaches the axis of the dome, the directions of principal propagation become steeper. Therefore, the axes of the folds turn also into progressively steeper directions until, at high levels in the dome, there should remain only a multitude of folds with nearly vertical axes. The nearly complete agreement between the orientation of Escher and Kuenen's experimentally produced folds, and those found in the mine seems to the writer a strong argument supporting the view that a salt dome like the present one, has indeed developed through the organized upward movement of salt layers through a vertical chim-

[4] As the rheological properties of such diverse substances as paraffine, china clay, various plastics, unconsolidated sediments, and crystal aggregates differ widely, whereas the deformation patterns under discussion are essentially identical, a general term is needed that avoids the narrower if more rigorously defined, meaning of plasticity, pseudo-elastic flow, elasticoviscous flow, consistency, thixotropy, structure-viscosity, and others. For this reason, the writer follows a suggestion by Goranson (35) in using a more general, less rigidly defined term. An interesting review of the various rheological definitions was recently given by G. W. Scott Blair (12).

ney. In fact it can be shown that practically no other mechanical process could have produced the fold pattern. Suppose, for example, that folds had formed at the base of the dome, with axes trending subhorizontally, but in tangential directions, after the manner of horizontal rings near the base of the dome. If salt with such folds advances higher into the dome, the axes should remain subhorizontal although the thickness and dip angles of limbs should be greatly deformed and modified. Supposing even that such folds had a more irregular original orientation and that they were flexed and drawn out in more than one direction through unequal rates of inward movement of adjacent masses of salt, one should still expect that at least some remnants of folds with flat axes would survive. Yet they seem to be completely lacking.

On the other hand, it is safe to assume that, with close approach to the axis of the dome, parts of many salt layers were puckered and twisted so intensely that they were finally reduced to strips and lenses parallel with the upward movement. To a certain extent, this has also been observed by Escher and Kuenen who show that entire groups of folds may be sheared off others (30, pp. 165–67). Each complex retains its vertical axes, but, in horizontal plan, has a different geometry of its limbs. We believe that much of the compact salt has originated through recrystallization of such marginal zones in which the layers have been obliterated, and contrasting patterns of limbs can be seen in many sections of the mine (J 6, L 8, J 11, I 4, J 12, and elsewhere).

Perhaps the sliding of individual groups of folds past each other helps to explain the origin of the few small closures (p. 1805). If two or more complexes of folds had become independent and then continued to move higher through the chimney, it is conceivable that layers below them might be drawn into a finger-like space near the junction plane of the higher layers, and there develop a small, local dome. If drawn high enough, between stronger adjacent masses, such a small dome might subsequently be squeezed and its sides be bent to conform with the surrounding surfaces. Possibly, the bent closures at D 2 and F 3 formed in such a way.

The scarcity of folds in the contact-near zone of the salt dome (AB 2–7) is not surprising for the proximity of the resistant roof must have acted as a stabilizing plane that reduced folding of one group of layers over another. It has its analog in the surface films of streaming fluids, and the marginal zones of schistosity in the contact zones of many plutons and diapirs (4, p. 629; 6, pp. 54–69; 10; 25; 29; 31; 40; 50; 56; 57; 65; 76; 88).

Shear folds.—Despite the large number of known salt domes, the movement of very large masses of crystals through the earth's crust, in the form of a dome, is a relatively rare phenomenon. It is therefore of great interest if certain phases of such a movement can be compared with similar features of deformation that are widespread in the earth's crust. The shear folds provide this means of comparison. Evidently, these planes have played nearly the same role in the deformation of the salt as do cleavage planes in slates and other incompetent rocks. As such,

they are oriented parallel with the axial planes of the folds in which they occur; and the measurable component of displacement along the shears, as described, has served to lengthen each fold parallel with the axial plane. Shears in the salt differ, however, from those in argillaceous rocks in that rupture does not seem to have occurred, at least not at the now exposed level. In other rocks, all gradations are found between nearly straight limbs of folds in which the shears cause only slight buckles, to rows of displaced fragments of the stronger interbeds, the difference depending on the thickness of the layers, the degree of difference in strength between the weakest and strongest layers, the magnitude of the shear stress and load, and the amount of friction between layers. The literature that deals with these problems is large (3, 5, pp. 709–14, 722, 723, 753; 11; 19, pp. 31, 90, 159, Pl. 1, Fig. 1, Figs. 15, 32, 53; 26; 42; 45; 49). So-called ptygmatic folds (14, pp. 163–65; 44; 78; 79), and boudinage (21, 71) are in some instances due to similar, closely spaced shear planes that have deformed more competent layers, with or without rupture. There seems to be a relationship between the grain size of the matrix, and the spacing of the slip planes. In slates, the cleavage planes commonly lie so close together that they can be counted only under medium or high magnification. In sandy slates from eastern New York, with an average grain size of the quartz of about 0.1 millimeter, slip planes are about 2 millimeters apart. In graywackes, with clastic quartz up to about 1 millimeter, shear planes are as much as 4–8 millimeters apart. In the Grand Saline mine, the slip planes seem to be about 10–15 millimeters (about $\frac{1}{2}$ inch) apart, although it may vary more, because almost all shear folds happen to be exposed on high, inaccessible ceilings, and the distances are accordingly difficult to estimate. Nevertheless, the spacing seems to have a similar, and perhaps significant, dependence on the average grain size of the salt aggregate (Fig. 22). Perhaps studies in other salt domes will clarify these relations.

It is to be hoped that some day, somewhere, a block of salt with the corrugated anhydrite layers in it will be secured. At Grand Saline, it was not obtainable. A block of this kind, in the hands of a skilled experimenter, may contribute significantly to our present knowledge of the amount of shear stress that will set in motion the slip planes. The shear folds reproduce, so to speak, the only, and unsuccessful, attempt to rupture the salt during its upward movement. It could be assumed that the planes die out downward at levels where the motion of the salt was free from throughgoing shear planes. Again, it would be interesting to know whether the planes cause actual displacement of the anhydrite layers at higher levels. As the mine operates one level only, this will probably never be known at Grand Saline, but such data can perhaps be gathered in other domes where several levels are accessible. As the large foreign literature shows, fractures and faults in salt are common at much lower levels than 700 feet (53, 80). It will probably never be possible to subject a slate block with interbeds of sandstone or limestone to the requisite strain to continue slip on already developed cleavage planes. Yet this may conceivably be possible with a block of rock salt for it lacks

a cementing substance, and what there is of it, has the same composition as the larger grains. Moreover, our knowledge of the deformation of halite is already far advanced. For this reason, it may perhaps be possible to establish the limiting conditions under which salt layers cease to fold without rupture, and throughgoing glide planes make their first appearance.

SMALL-SCALE MOTION

Deformation of anhydrite.—The large-scale movement of salt through the dome is, of course, the combined result of the motion of immense numbers of individual crystals. It is desirable to trace the deformation from large-scale to small-scale phenomena. If we can discover analogs with deformational structures in other rocks, and connect them with other, similar processes in the earth's crust; and should find that the similarities extend to large as well as small scales, the hypothetical picture of the evolution of salt domes becomes more reliable.

The alignment of anhydrite crystals is a case in point. As far as we have been able to ascertain, anhydrite in undeformed, flat salt beds has the same range in size and crystallographic habit as the grains in domes. It may be assumed, therefore, that these small crystals are carried passively, suspended in the halite aggregate. At any rate, we have failed to find evidence that these crystals have grown appreciably while they were embedded in the salt. The very definite alignment of these small prismatic crystals in directions that coincide with the orientation of the fold axes and approach that of the axis of the dome as closely as can be expected, in view of the size and steeply conical shape of it, leaves little doubt that the movements of the small interpositions were systematically coordinated to the large-scale motion of the salt mass through the dome. The preferred orientation of the anhydrites has its exact counterpart in the alignment of prismatic phenocrysts in igneous plugs parallel with the axis of the plug, the subvertical alignment of pebble axes, prismatic minerals, and metacrysts along the borders of plutons and diapirs, and the preferred orientation of prismatic suspensions parallel with the axis of a pipe in which a fluid is flowing (6, pp. 87–90; 23–25; 59; 72). It has a further analog in the rolling textures of steel and other alloys, in which the more brittle admixtures, due to the simultaneous effects of compression and stretching, are drawn out in streaks parallel with the direction of rolling (73, 41, p. 172; 7, pp. 395–408), and may or may not be flattened parallel with the rolling plane. Still another comparable orientation is that of the "seeds" (small bubbles) in rolled glass. They, too, are elongate parallel with the direction of rolling.[5] A linear texture, parallel with the axes of folds, was observed by Escher and Kuenen in their experiments with paraffine and china clay. It is described as "longitudinal grooves" and "creased appearance" (30, pp. 164, 165, 170, 171, Pl. 33, Figs. 31, 33, Pl. 37, Fig. 48, Pl. 24). The stretching of their material in the direction of the lineation was particularly noticeable through the

[5] Letter to the writer, dated July 1, 1946, by J. C. Hostetter, president, Mississippi Glass Company, St. Louis, Missouri.

development of tension cracks at right angles to the axes of the folds (30, p. 163, Pl. 34, Fig. 37, p. 165). Taylor (87, p. 39) mentions trains of anhydrite cleavage fragments, suggesting that they have been pulled apart by the motion of the surrounding material. In the slides examined in the present study, this particular feature was not found, but a more comprehensive microscopical examination of the salt may well bring to light more examples of this kind.

Deformation of halite.—This leaves the halite crystals as the principal carriers of the deformation of the salt dome. It is remarkable that the microscope shows an aggregate of unstrained isotropic crystals, despite the manifest evidence of immense mechanical deformation. It is worth while to review briefly present information on this seemingly contradictory condition.

Under stress, halite crystals deform by slip on the six dodecahedron planes, (110) in the direction, $[1\bar{1}0]$, (74, p. 165; 75, pp. 240–41; 7, p. 297). As we wish to know how salt will behave under unequal load, the most important point is the determination of the least shearing stress that will cause permanent deformation of halite crystals. This matter has been the subject of many investigations, and difficult to determine. There is agreement that dry, impure halite is stronger than dry, pure halite; that enclosed water increases its strength greatly; that previously strained salt is stronger than unstrained salt; and that salt at low temperatures is stronger than at high temperatures. Whether an aggregate of small halite crystals is stronger, as strong, or weaker than a single crystal, does not yet seem to be clear. Most of the pertinent data are discussed by Schmid and Boas (75, pp. 238–71), who cover the literature to 1935.

In 1934, Nettleton (60) presented his well known theory explaining the rise of salt domes by the effects of shearing stresses generated by a difference in load of two adjacent theoretical columns of rock. His Figure 1 (60, p. 1179) gives the differences in hydrostatic pressure between columns of various aggregate specific gravities.

We wish to know under which favorable conditions the originally flat, undeformed salt layer may have been able to produce the first doming of its roof. Though the relevant facts and figures are not precise enough to give a complete solution, they do permit us to describe the nature of the conditions in approximate terms.

Figure 24 shows a salt layer, 700 feet thick, under 15,000 feet of sediments. On the left, a column, A, is singled out. It is assumed to have a bulk specific gravity of 2.5. Therefore, at the base of this column, the salt stands under a pressure of $p_A = 1{,}144$ kg./cm.[2] On the right, column B is assumed to have a bulk specific gravity of 2.36, so that the salt at its base stands under a pressure of $p_B = 1{,}079$ kg./cm.[2] If the salt behaved like a fluid, it would transmit the pressure p_A, to all its parts, so that at point B the pressure exerted by the salt against the base of the sedimentary column would exceed by 65 kg./cm.[2] the pressure of the sediments on the salt.

How great must this excess pressure be in order to deform the salt, that is,

to produce the first buckling of the sedimentary cover upward? The salt must not only overcome its own internal friction, but must also lift its roof rocks and deform them. Nettleton (60, p. 1184) and Dobrin (27) have shown that the ease with which the roof is deformed, depends on the viscosity properties of the roof rocks. But neither it nor the internal friction of the salt can be stated in exact figures. However, the least shear stress is known that will cause permanent deformation of salt aggregates. In a series of important experiments, Walter

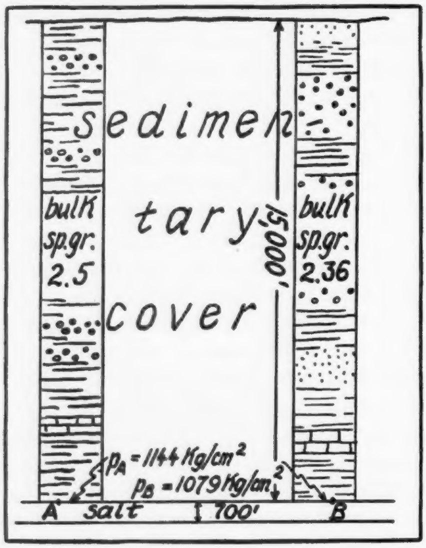


FIG. 24.—Diagram to illustrate conditions under which a salt dome may begin to form. Two columns of sedimentary rocks differ in bulk specific gravities by 0.14. If they are 15,000 feet high, the heavier column, at A, will exert on salt a compressive stress of 1,144 kg./cm.², whereas lighter column, at B, will produce compressive stress of 1,079 kg./cm.², or 65 kg./cm.² less than that at A. If the salt is assumed to transmit pressure at A like a fluid, salt at B would exert compressive stress of nearly 1,144 kg./cm.² on base of sediments. Greatest shear stress component of this excess pressure, namely 30 kg./cm.², is adequate to cause permanent deformation in salt. Therefore, under favorable conditions a dome might be initiated at B.

Schmidt (77) has found that a least shear stress of 30–40 kg./cm.² will start plastic deformation of halite. Similar experiments by Stöcke and Borchert (84) gave figures of 30–50 kg./cm.², and earlier determinations by Joffé, Kirpitschewa, and Lewitzky (46, p. 286; 47, p. 62) gave similar to slightly higher values. As every compressive stress can be imagined to generate two equivalent shear stresses, a mass of salt should be under an excess compression of at least 60 kg./cm.² in one direction, in order that slip along favorably oriented glide planes of its crystals may commence. It will now be seen that if the two theoretical, adjacent col-

umns differ in bulk specific gravity by 0.13–0.14, at the base of the lighter column a pressure differential of very nearly 60 kg./cm.^{2} may develop (59 kg./cm.^{2} for 0.13, and 65 kg./cm.^{2} for 0.14). This pressure differential, divided by two, would give the least shear stress necessary to cause permanent deformation of some crystals.

Peters and Dugan (66, pp. 382, 391) report that samples of sedimentary cover rocks, collected at the surface, and drill-core specimens, down to depths of 8,600 feet, vary in specific gravity from 2.10 to 2.66 but beyond this one can only guess what combination of light layers or lenses of sediment may have so reduced the bulk specific gravity of a particular section that the requisite pressure difference was created at the top of the salt. One might imagine that a section of particularly porous, dry sediment would be a favorable area for the initiation of a dome. We have not gone through the large stratigraphic literature of the Texas Gulf Coast to see whether such variations of porosity, composition, and amount of ground-water flow are common, or very rare in other places.

The conditions favorable for initiation of a salt dome could be improved if a particularly light column of rock is surrounded by a uniformly heavy sequence of layers; or if the salt layer already had a local "high" in its original surface; or if the mother layer was appreciably thicker in one area, for this would probably reduce the internal friction of the moving salt. It should also be kept in mind that the geothermal gradient at a depth of 15,000 feet may raise the temperature of the salt to about 350°F. (177°C.), which very probably reduced the shear strength of the salt, so that a pressure differential of less than 60 kg./cm.^{2} may have sufficed to initiate doming.

Concluding, one may say that the geological environment seems nearly adequate to produce the mechanical conditions under which a salt dome may begin to rise. Nevertheless, it would be desirable to have in reserve, so to speak, a certain margin of safety that might increase one's confidence that the process here envisaged, has been competent to lift the roof, and that the depths of 3 or more miles at which the movement is thought to have started, are adequate to generate sufficiently large shear stresses. We believe that the creep of halite provides this safety factor, but present data permit only a guess of how effective it may be.

Creep.—"There is a rather clearly defined stress at which a given crystal will begin to flow at an appreciable rate. Below this stress the rate of strain is so slow it requires long-time tests to measure it. In this range the flow is creep" (7, p. 294; see also p. 344). Creep in halite has not yet been tested extensively. Griggs (33, pp. 241–42) refers to an experiment with a single crystal. It was compressed at 61 kg./cm.^{2} (corresponding approximately to a shear stress of 30 kg./cm.^{2}) for 42 days. The compressed side was 0.021 cm. shorter than before, and "of this, only 0.00021 inch, or 0.026 per cent is attributed to pseudoviscous flow."[6] The stress chosen is nearly identical with Schmidt's least shear stress, and thus does not increase our knowledge significantly.

[6] Letter from David Griggs to the writer, dated April 7, 1949.

The elastic limit of halite, based on determinations by A. Smekal and others, is generally given as between 3.7 and 15 kg./cm.^{2}, depending on the method of determination and degree of purity of the material. Thus there is an appreciable gap between the elastic limit and the least shear stress of about 30 kg./cm.^{2} that produces permanent deformation of halite in short-time experiments. At the moment, there does not seem to be enough information on the behavior of halite in this pressure field to justify more than a guess of what might be found. Nevertheless, at the conclusion of their tests with halite, Stöcke and Borchert have the following to say (translated by the writer).

> Especially the results of experiments of long duration justify the assumption that the values for stresses obtained in the laboratory, represent *maximum* values for the inception of rock deformation; and that very probably even small deviations from a field of hydrostatic pressure, and small effects of a pressure in excess of confining stress, if applied over long geologic periods, will generate flow phenomena. Perhaps a shear stress of 30 kg./cm.^{2}, at a temperature corresponding to the geothermal gradient, can permanently deform rock salt, if not noticeably in one year, then in a century; especially if each single grain is healed over and over by recrystallization. At present, no final data are available on this point. But certain it is that the influence of time is only directed toward a reduction of the shearing strength (84, p. 216).

With this in mind, one may picture the mother salt bed under a load which was sufficiently reduced at certain points that the stress differential set in motion permanent slip on dodecahedron planes of millions of halite crystals. One component of a majority of these slip movements was presumably directed upward, so that the roof began to yield very slowly, giving rise in due time to the first domal protrusion of the upper salt contact.

How fast did the salt rise? If Holmes' latest figures for the duration of geologic periods are used (43), and if it is assumed that the movement began in early Cretaceous time, we have about 120 million years for the movement. Assuming that the shortest distance to rise was about 3 miles (15,840 feet), we have

15,840 feet per 120 million years, or
132 feet per 1 million years, or
0.158 inches (3.95 mm.) per century, or
0.04 millimeter per year, or
0.0001 millimeter per day.

The actual movement must have been faster for a large volume of salt has probably streamed through the chimney, and if the radius of the hypothetical gathering area, 6 miles (p. 1813), is considered, a rate of movement of about 0.08 millimeter per year, or 0.0002 millimeter per day, may be a better approximation.

It is interesting that much faster movement of rock salt has been measured in mines. In 1907, director Bernhard Busch of the Neu-Stassfurt mine in Germany published a series of measurements of plastic salt deformation (16). Figure 25 lists his findings. His attention to salt movement was aroused by the inward bending of the walls of a newly excavated shaft. Thereupon the interior

diameters of crosscuts, about 300 feet (100 meters) from the shaft, were gauged, at a depth of 2,460 feet (750 meters). It will be seen that salt was capable of extruding at speeds as much as 0.13 and 0.9 millimeters per day—many hundreds of times faster than needed in the foregoing picture. Busch also had holes drilled into the walls, 40 millimeters in diameter, and 50 centimeters deep. These were filled with lead bars that just fitted when they were inserted, and the time was recorded when they jammed. At 500 meters depth (1,640 feet), the bars jammed after a few months; at 300 meters depth (984 feet), the bars jammed after 2 years; and above 250 meters depth (820 feet), the holes stayed open.

A report by Georg Spackeler (83, pp. 66–67) is also of interest. He states that in salt mines in the Austrian Salzburg district, old tunnels were discovered in

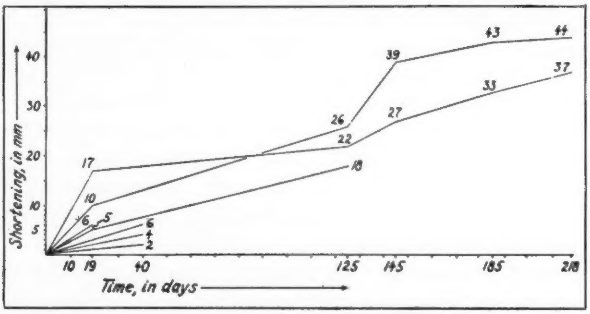


FIG. 25.—Graphic representation of Busch's measurements of plastic flow of salt, in tunnels of the Neu-Stassfurt mine. Ordinate gives shortening of tunnel diameters, as gauged. Long curves represent shortening of horizontal diameters, shorter curves are changes in vertical diameters. Figures in chart give shortening in millimeters.

which bodies of ancient Celtic miners were found with their mining tools, embedded in salt. Unfortunately, the original reference is not given by Spackeler. His description does not exclude the possibility that the embedding was caused by slip of salt clay which is known to occur in the Salzburg district, nor is it specifically stated that the embedding salt could not have been a pile of salt fragments that may have collapsed upon the miners, and that subsequent cementation by mine waters created the impression that this pile of salt had protruded plastically over the bodies, as Spackeler believes. Nevertheless, if the slowest rate of plastic flow in Busch's figures is used, 5 millimeters in 106 days (0.048 millimeter per day), a salt wall might protrude as much as 3.5 meters or 11.5 feet, in 2,000 years. Even one half of this value might suffice.

Most of the North American mines in salt domes are of very recent date, and few operate at depths below 1,000 feet. The chances of discovering traces of plastic flow, therefore, are not good, especially as the vibrations set up by heavy blasting, cause large-scale fracturing parallel with the walls of rooms in many

instances. Nevertheless, we have seen timbers, more than 6 inches thick, bent and broken by movement of the salt behind it, and drill holes with appreciably reduced diameters. If in some abandoned tunnels of a few mines a few of the sensitive new strain gauges could be set up, our knowledge of slow movement of salt masses in domes might be significantly increased. Though it does not seem possible to measure directly a rate of upward motion, it might be possible to learn the magnitude of internal strain, especially in salt "spines."

Strain-hardening, and recrystallization.—All experimenters agree that halite crystals become stronger as they are being deformed by slip. In other words, strain-hardened crystals resist further deformation, so that a greater and greater shear stress is required to overcome this resistance. In Schmidt's experiments, a stress of as much as 275 and 300 kg./cm.^{2} was needed to maintain deformation (77, p. 11). This strength approaches that of limestone. On the other hand, he found that mere increase in the compressive stress is of very little significance.

We may therefore amplify the theoretical picture of a salt mass that begins to form a dome, and assume that in the aggregate those particular crystals will slip first, in which the effective component of the shear stress lies closest to the direction of slip on the dodecahedron planes. As there are six equivalent ones in each crystal, it may be assumed that that particular direction will first be utilized that lies most nearly parallel with the direction of easiest relief—in this case probably upward. Other directions may be utilized in succession.

Crystal grains that have been so deformed, may be supposed to retire for some time from further deformation, on account of their incipient strain-hardening. In the meantime, their neighbors, whose orientation made them less susceptible to strain at the beginning of the deformation process, may now take over, and in due time the entire salt mass should have slipped, so that all crystals have become strain-hardened. Should that happen, a shear stress of increasing magnitude only could keep the salt deformation up.

In order to propagate the entire salt mass through the dome, the mass of each crystal must slip many times. In order that a crystal lose its strain-hardening, it is necessary that the ions whose positions have been locally disturbed by the slip, return to new, normal positions. The process is known as recrystallization, and has been the subject of several investigations. We wish to know how soon after deformation, and through what circumstances, a crystal may return to a recrystallized condition, in order to lose its strain-hardening, and to be able to slip again under a relatively low shear stress.

Ingression of water would be a simple means of depositing crystals with relaxed, normal lattices from brine. There is, however, no evidence that in this dome brine circulation, even on a limited scale, has been of any significance. It is more probable that an essentially dry aggregate of crystals has at all times been the carrier of the deformation. Aggregates of strain-hardened halite crystals, when heated for about 168 hours at 100°–200°C., lose the strain-hardening (77, p. 22). If the generally accepted geothermal gradient of about 1°F. per 50 feet

is applied, the salt at a depth of 15,000 feet might be at a temperature of about 350°F. (*ca.* 177°C.). If so, it would recrystallize promptly and remain a very weak substance. At higher levels, both temperatures and rates of recrystallization decrease, though exactly at what rate is not known. Salt aggregates which Schmidt had strain-hardened to a fairly high amount, and laid aside at room temperatures for a half year, failed to show weakening due to recrystallization when tested again. Their deformation curve rose purely elastically to the highest shear stress to which the material had been exposed, and then flattened out, indicating the beginning of plastic flow; a knickpoint separated the two branches of the curve (77, p. 22).

Similar tests have been made by J. Leonhardt (52). Specimens of natural salt from mines were powdered, compressed under 500–30,000 kg./cm.^{2}, and subsequently heated at different temperatures and over varying periods. The degree of lattice orientation was at all stages tested with x-ray diagrams. He reports (52, p. 85) that both sodium chloride and potassium chloride begin to recrystallize at room temperatures if the preceding applied stress has been high enough. A specimen, for instance that had been compressed at room temperature for 1 hour at 10,400 kg./cm.^{2}, had completely recrystallized after 720 hours (1 month). Another specimen, compressed for 1 hour under 500 kg./cm.^{2}, had begun to recrystallize after 20 days at 100°C. In contrast to the two halogen salts, anhydrite did not begin to recrystallize below 600°C. Leonhardt also tested the compressive strength of strain-hardened halite and sylvite before and after tempering, and found that the heating lowered the strength appreciably (52, p. 91).

Burgers (15, p. 192) summarizes earlier experiments by Müller (58) and Przibram (70) who endeavored to determine the speed with which recrystallization progresses in previously compressed halite single crystals, as well as crystal aggregates. Figures obtained under heat and pressure conditions that exceed greatly what may be expected in our case, are of little interest, but a few experiments approach geological conditions closely. A group of specimens had been compressed at 200 kg./cm.^{2}; at a temperature of 100°C., a speed of recrystallization of 0.0038 mm./min. was found; at 200°C., the speed was 0.022 mm./min.; and at 18°C., it was 0.00006 mm./min. (=31.5 mm./year). These speeds are far in excess of what is needed in the picture of a salt aggregate moving through a salt dome, and all experimenters agree that impurities in the salt, and decrease in compressive stress will appreciably slow down the speed of recrystallization. It seems to the writer, however, that the order of magnitude of these figures comes close to what is to be expected under geological conditions, and if the movement proceeded at the rate generally estimated, it would explain satisfactorily why the halite aggregate fails to exhibit strain birefringence under the microscope, despite the strong evidence of large mechanical deformation. On the other hand, it should be expected that among very many crystals, a few would be strained, namely, those that have been slipping so recently that they have not yet recrystallized. A systematic examination of a large number of thin sections, collected

from the most likely places in the mine, might bring to light such grains. It should also be possible to determine to what extent strain is optically reproduced. For instance, in the immediate vicinity of blasts, or at places where salt has spalled due to blasting, strained grains may be located. If they should be entirely lacking it might be worth investigating whether perhaps the borders of anhydrite zones show greater strain than other zones of purer salt. It should also be kept in mind that at the shallow levels at which most of the Gulf Coast salt mines operate, the salt is not any longer in a very active zone of plastic flow, and that accordingly the number of strained crystals is bound to be very small.

The last question is the reason for the distorted shape of so many halite crystals. The writer does not have enough evidence for more than a few suggestions. The answer is difficult because we do not seem to know at present whether the elongate halite grains are preferentially oriented. In the available time it was not possible to make systematic observations on mine walls to determine any preferred crystallographic orientation of halite crystals. We gained the impression that many grains had a cube edge, or the pole to the octahedron plane, upward, and looked in vain for grains that had the cube face up. To decide this matter, a systematic statistical study is needed, far beyond what the writer intended to do. It is also possible that the elongation of so many grains parallel with the axis of movement has been brought about by deformation of each crystal into the most stable shape, so that rotational moments on its flanks became a minimum. Such a group of sheared plates could then have recrystallized into the almond-shaped grains that are seen on the mine walls. Such deformation of aluminum crystals has been studied and illustrated by Seidl and Schiebold (82, pp. 320–23). Perhaps that of halite is not unlike it, but more work is necessary before an answer can be given. To which extent Riecke's principle may be applicable, is likewise difficult to say as long as the crystallographic orientation of the grains is unknown, and the presence of films of brine on the crystal surfaces is, to say the least, most difficult to prove.

CONCLUSIONS

In our opinion, the large-scale and the small-scale deformation phenomena in the exposed part of the salt dome are satisfactorily explained by the motion of a layered salt-anhydrite mass upward through the dome. We do not believe that any other process can bring about the identical orientation of so many heterogeneous structural features.

A review of the literature, although admittedly incomplete, suggests that an aggregate of halite, given sufficient load differentials, will commence upward plastic flow at depths of about 3 miles, provided it can overcome the resistance of the roof. Available data on strain-hardening, rates of recrystallization, and plastic deformation of halite seem compatible with the fact that the halite aggregate fails to exhibit strain birefringence despite compelling evidence of great mechanical deformation.

The initial formation of the layered saline series, the factors that may have determined the location of the dome, the origin of the cap rock, and the possible role that forces other than density difference may have played in bringing about the rise of the salt, are considered outside the scope of this paper.

REFERENCES

1. ANDREATTA, CIRO, "Analisi strutturali di rocce metamorfichi," Pt. II, *Periodico di Mineralogia*, Vol. 4 (1933), No. 1.
2. BAILEY, JAMES, "Stretch Orientation of Styrene and Its Interesting Results," *India Rubber World*, Vol. 118 (1948), pp. 225–31.
3. BAIN, G. W., "Flowage Folding," *Amer. Jour. Sci.*, Vol. 22 (1931), pp. 503–30.
4. BALK, ROBERT, AND GROUT, F. F., "Structural Study of the Snowbank Stock," *Bull. Geol. Soc. America*, Vol. 45 (1934), pp. 621–36.
5. BALK, ROBERT, "Structural and Petrologic Studies in Dutchess County, N. Y., Pt. 1: Geologic Structure of Sedimentary Rocks," *ibid.*, Vol. 47 (1936), pp. 685–774.
6. ———, "Structural Behavior of Igneous Rocks," *Geol. Soc. America Mem. 5* (1937). 177 pp.
7. BARRETT, C. S., *Structure of Metals*. McGraw-Hill Company, New York (1943). 567 pp.
8. BARTH, T. F. W., AND LUNDE, G., "Der Unterschied der Gitterkonstanten von Steinsalz und von chemisch reinem Natriumchlorid," *Zeitschr. Phys. Chemie*, Vol. 126 (1927), pp. 417–24.
9. BARTON D. C., "Petrographic Study of Salt Dome Cap Rock," *Gulf Coast Oil Fields*, Amer. Assoc. Petrol. Geol. (1936), pp. 42–43.
10. BATEMAN, J. D., "Sheridan Map Area, Manitoba," *Canada Geol. Survey Paper 45–15* (1945), p. 4.
11. BEHRE, C. H., JR., "Slate in Pennsylvania," *Pennsylvania Geol. Survey Bull. M. 16* (1933), pp. 36–39.
12. BLAIR, G. W. S., *A Survey of General and Applied Rheology*. Pitman, New York (1944). 196 pp.
13. BUDDINGTON, A. F., AND RUEDEMANN, RUDOLF, "Geology and Mineral Resources of the Hammond, Antwerp, and Lowville Quadrangles," *N. Y. State Mus. Bull. 296* (1934). 251 pp.
14. BUDDINGTON, A. F., "Adirondack Igneous Rocks and Their Metamorphism," *Geol. Soc. America Mem. 7* (1939). 354 pp.
15. BURGERS, W. G., "Rekristallisation, Verformter Zustand und Erholung," *Masing's Handbuch der Metallphysik*, Vol. 3 (1941), p. 192.
16. BUSCH, BERNHARD, "Etwas über die Expansivkraft des Salzes," *Zeitschr. f. Prakt. Geol.*, Vol. 15 (1907), pp. 369–71.
17. CHENEY, C. A., "Salt Domes of Northeastern Texas," *Oil and Gas Jour.*, Vol. 20, No. 32 (1932), pp. 82–83.
18. CLOOS, ERNST, "The Loon Lake Pluton, Bancroft Area, Ontario, Canada," *Jour. Geol.*, Vol. 42 (1934), pp. 393–99.
19. ———, AND ANNA HIETANEN, "Geology of the 'Martic Overthrust' and the Glenarm Series in Pennsylvania and Maryland," *Geol. Soc. America Spec. Paper 35* (1941). 207 pp.
20. ———, "Lineation—A Critical Review and Annotated Bibliography," *Geol. Soc. America Mem. 18* (1946). 122 pp.
21. ———, "Boudinage," *Trans. Amer. Geophys. Union*, Vol. 28 (1947), pp. 626–32.
22. BROEDEL, C. H., "The Structure of the Gneiss Domes Near Baltimore, Maryland," *Maryland Geol. Survey*, Vol. 13 (1937), pp. 149–87.
23. CLOOS, HANS, AND CLOOS, ERNST, "Die Quellkuppe des Drachenfels am Rhein," *Zeitschr. f. Vulkanol.*, Vol. 11 (1927), pp. 33–40.
24. ———, "Das Strömungsbild der Wolkenburg im Siebengebirge," *ibid.*, pp. 93–95.
25. CLOOS, ERNST, "Tectonic Transport and Fabric in a Maryland Granite," *Comm. Géol. de Finlande Bull. 140* (1947), pp. 1–14.
26. DALE, T. N., "The Slate Belt of Eastern New York and Western Vermont," *U. S. Geol. Survey Ann. Rept.*, Vol. 19 (1899), Pt. 3, pp. 213–15.
27. DOBRIN, M. B., "Some Quantitative Experiments on a Fluid Salt-Dome Model and Their Geological Implications," *Trans. Amer. Geophys. Union*, Vol. 22 (1941), Pt. 2, pp. 528–42.
28. CUSHING, H. P., AND NEWLAND, D. H., "Geology of the Gouverneur Quadrangle," *New York State Mus. Bull. 259* (1925). 122 pp.
29. ECK, BRUNO, *Strömungslehre an Hand von Strömungsbildern*. Privately published, Cologne (1931). 16 pp., 60 Figs.
30. ESCHER, B. G., AND KUENEN, P. H., "Experiments in Connection with Salt Domes," *Leidsche Geologische Mededeelingen*, Deel 3, Aflevering 3 (1929), pp. 151–82, Pls. 20–38.
31. FAIRBAIRN, H. W., "Elongation in Deformed Rocks," *Jour. Geol.*, Vol. 44 (1936), pp. 670–80.
32. ———, *Structural Petrology of Deformed Rocks*. Addison-Wesley Press, Inc., Cambridge, Massachusetts (1942). 143 pp.

33. GRIGGS, DAVID, "Creep of Rocks," *Jour. Geol.*, Vol. 47 (1939), pp. 225–51.
34. GOLDMAN, M. I., "Origin of the Anhydrite Cap Rock of American Salt Domes," *U. S. Geol. Survey Prof. Paper 175* (1933), pp. 83–114.
35. GORANSON, R. W., "Fracture and Flow in Stressed Solids," *Trans. Amer. Geophys. Union*, Vol. 21 (1940), Pt. 1, pp. 698–700.
36. HANNA, M. A., "Geology of the Gulf Coast Salt Domes," *Problems of Petroleum Geology*, Amer. Assoc. Petrol. Geol. (1934), pp. 629–78.
37. HARTWIG, G., "Stratigraphie und Tektonik des Kaliwerkes 'Siegfried-Giesen' bei Hildesheim," *Kalifestschrift zum 70. Geburtstag von Heinrich Precht* (1922), pp. 1–21. Hannover.
38. ———, "Die Salz- 'Seismogramme,' ihre tektonische und praktische Bedeutung," *Kali, Verwandte Salze, und Erdöl*, Vol. 17 (1923), pp. 193–97.
39. HAZZARD, R. T., SPOONER, W. C., AND BLANPIED, B. W., "Notes on the Stratigraphy of the Formations which Underlie the Smackover Limestone in South Arkansas, Northeast Texas, and North Louisiana," *Shreveport Geol. Soc. 1945 Reference Report*, Vol. 2 (1947), pp. 483–503.
40. HENDERSON, J. F., "Structure and Metamorphism of Early Pre-Cambrian Rocks between Gordon and Great Slave Lakes, Northwest Territories," *Amer. Jour. Sci.*, Vol. 241 (1943), pp. 430–46, esp. p. 445.
41. HEYER, R. H., *Engineering Physical Metallurgy*, p. 172. Van Nostrand Company, New York (1940).
42. HILLS, E. S., *Outlines of Structural Geology*, pp. 98–100. Methuen Company, London (1940).
43. HOLMES, ARTHUR, "A Revised Estimate of the Age of the Earth," *Nature*, Vol. 159 (1947), p. 127.
44. HOLMQUIST, P. J., "Om Pegmatitpalingenes och Ptygmatisk Veckning," *Geol. Fören. Förh.*, Vol. 42 (1920), pp. 191–213.
45. ———, "The Relative Plasticity of Rock Masses under the Influence of Dynamic Deformation," *Fennia*, Vol. 50 (1928), No. 33. 13 pp.
46. JOFFÉ, A. F., KIRPITSCHEWA, M. W., AND LEWITSKY, M. A., "Deformation und Festigkeit der Kristalle," *Zeitschr. f. Physik*, Vol. 22 (1924), p. 286.
47. JOFFÉ, A. F., *Thy Physics of Crystals*, p. 62. McGraw-Hill Company, New York (1928).
48. KENNEDY, W., "A Section from Terrell, Kaufman County, to Sabine Pass on the Gulf of Mexico," *Geol. Survey Texas 3d Ann. Rept.* (1891), pp. 41–125.
49. KIENOW, SIGISMUND, "Grundzüge einer Theorie der Faltungs- und Schieferungsvorgänge," *Fortschr. d. Geol. und Paläont.*, Vol. 14, No. 46 (1942). 129 pp. (A translation of this mathematical treatise into English by Balk is in preparation.)
50. KRAUSKOPF, K. B., "The Wallowa Batholith," *Amer. Jour. Sci.*, Vol. 241 (1943), p. 616.
51. LAMCKE, KURT, "Gefügeanalytische Untersuchungen am Anhydrit, nebst einem Beitrag zu den optischen und roentgenoptischen Methoden der Gefügeanalyse," *Schriften aus dem Mineral. Inst. d. Univ. Kiel*, Heft 4 (1936), pp. 1–39. Original not obtainable to the writer. Résumé in: *N. Jahrb. f. Mineral., etc., Referate*, Vol. 1 (1937), pp. 597–98.
52. LEONHARDT, J., "Gefüge und Umformung von Salzmassen mit Bezug auf Vorgänge die an den festen Zustand gebunden sind," *Kali, Verwandte Salze, und Erdöl*, Vol. 31 (1937), No. 9, pp. 81–86, 91–94, 101–03.
53. LOTZE, FRANZ, *Steinsalz und Kalisalze*. 936 pp., with extensive bibliographies. Borntraeger, Berlin (1938). (This is Vol. 3, No. 1, of O. Stutzer's *Die Wichtigsten Lagerstätten der Nicht-Erze*).
54. MACKIN, J. H., "Some Structural Features of the Intrusions in the Iron Springs District," *Guidebook to the Geol. of Utah*, No. 2 (1947), Utah Geol. Soc., Salt Lake City. 62 pp.
55. MARTIN, J. C., "The Precambrian Rocks of the Canton Quadrangle," *New York State Mus. Bull. 185* (1916). 112 pp.
56. MAYO, E. B., "Some Intrusives and Their Wall Rocks in the Sierra Nevada," *Jour. Geol.*, Vol. 45 (1937), p. 686.
57. MRAZEC, L., "Les Plis diapirs et le Diapirisme en Général," *Inst. Géol. de Roumanie, C.-R. des Séances*, Vol. 6 (1914–1915), pp. 226–70. Bucarest (1927).
58. MÜLLER, H. G., "Zur Natur der Rekristallisationsvorgänge," *Zeitschr. f. Physik*, Vol. 96 (1935), Pt. 1: "Einkornrekristallisation an verformten Einkristallen," pp. 279–306; Pt. 2: "Untersuchungen an Rekristallisationseinkristallen," pp. 307–20; Pt. 3: "Versuche an Steinsalzpresskörpern," pp. 321–27.
59. NADAI, A., *Plasticity*, pp. 331–35. McGraw-Hill, New York (1931).
60. NETTLETON, L. L., "Fluid Mechanics of Salt Domes," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 18 (1934), pp. 1175–1204.
61. ———, "Recent Experimental and Geophysical Evidence of Mechanics of Salt-Dome Formation," *Bull. Amer. Assoc. Petrol. Geol.* Vol. 27 (1943), pp. 51–63.
62. ———, AND ELKINS, T. A., "Geologic Models Made from Granular Materials," *Trans. Amer. Geophys. Union*, Vol. 28 (1947), pp. 451–66.
63. NEWLAND, D. H., "Illustrations of the Deformation of Limestone under Regional Compression," *Bull. Geol. Soc. America*, Vol. 28 (1917), p. 163 (abstr.)

64. ———, "Plastic Deformation of Grenville Limestone," *New York State Mus. Bull. 196* (1918), pp. 145–47.
65. NICOLESCU, C. P., "Anticlinaux Diapirs Sédimentaires, Volcaniques et Plutoniques," *C. R. Somm. des Séances, Soc. Géol. de France* (1929), pp. 21–24.
66. PETERS, J. W., AND DUGAN, A. F., "Gravity and Magnetic Investigations at the Grand Saline Salt Dome, Van Zandt County, Texas," *Geophysics*, Vol. 10 (1945), pp. 376–93.
67. PHALEN, W. C., "Salt Resources of the United States," *U. S. Geol. Survey Bull. 669* (1919). 284 pp.
68. POWERS, SIDNEY, AND HOPKINS, O. B., "The Brooks, Steen, and Grand Saline Domes, Smith and Van Zandt Counties, Texas," *U. S. Geol. Survey Bull. 736-G* (1922), pp. 179–239.
69. POWERS, SIDNEY, "Interior Salt Domes of Texas," *Geology of Salt Dome Oil Fields*, Amer. Assoc. Petrol. Geol. (1926), pp. 225–31.
70. PRZIBRAM, KARL, "Über die Rekristallisation des Steinsalzes," *Zeitschr. f. Physik*, Vol. 67 (1931), pp. 89–105.
71. QUIRKE, T. T., "Boudinage, an Unusual Structure Phenomenon," *Bull. Geol. Soc. America*, Vol. 34 (1923), pp. 649–60.
72. RIEDEL, W., "Das Aufquellen Geologischer Schmelzmassen als Plastischer Formänderungsvorgang," *N. Jahrb. f. Mineral., etc., Beil.-Bd.*, Vol. 62, Abt. B (1929), pp. 151–70.
73. SAUVEUR, ALBERT, *The Metallography and Heat Treatment of Iron and Steel*, p. 185, Fig. 152; p. 192, Fig. 161; p. 193, Fig. 162. McGraw-Hill, New York (1935).
74. SCHMID, E., "On Plasticity, Crystallographic and Non-Crystallographic," *Intern. Conf. on Physics*, Vol. 2 ((The Solid State of Matter), London Phys. Soc. (1935), pp. 161–70.
75. ———, AND BOAS, W., "*Kristallplastizität*." 373 pp. Springer, Berlin (1935).
76. SCHMIDEGG, OSKAR, "Steilachsige Tektonik und Schlingenbau auf der Südseite der Tiroler Zentralalpen," *Jahrb. d. Geol. Bundesanst.*, Vol. 86 (1936), pp. 115–50. Vienna.
77. SCHMIDT, WALTER, "Festigkeit und Verfestigung von Steinsalz," *Zeitschr. f. Angew. Mineral.*, Vol. 1 (1939), pp. 1–29.
78. SEDERHOLM, J. J., "Über Ptygmatische Faltung," *N. Jahrb. f. Mineral., etc., Beil.-Bd.*, Vol. 36 (1913), pp. 491–512.
79. ———, "On Migmatites and Associated Pre-Cambrian Rocks of Southwestern Finland," *Comm. Géol. de Finlande Bull. 77* (1926), pp. 72–78.
80. SEIDL, E., "Die Permische Salzlagerstätte im Graf Moltke Schacht," *Archiv f. Lagerstättenforschung* (Berlin), Vol. 10 (1914). 104 pp.
81. ———, "Die Geologischen Gesetzmässigkeiten, welche im Hessisch-Thüringischen (Werra-Fulda) Gebiet für den Zechstein-Kalibergbau Massgebend sein müssen," *Kali, Verwandte Salze und Erdöl*, Vol. 17 (1923), p. 73, Figs. 19a-c; p. 88, Figs. 26a, 28.
82. ———, AND SCHIEBOLD, E., "Das Verhalten inhomogener Aluminiumgussblöckchen beim Kaltwalzen,—Makroskopische Verfolgung der Entstehung einer Walztextur," *Zeitschr. f. Metallk.*, Vol. 17 (1925), pp. 320–23, Figs. 31–45.
83. SPACKELER, GEORG, *Kalibergbaukunde*, pp. 66–67. W. Knapp, Halle (1925).
84. STÖCKE, K., AND BORCHERT, H., "Fliessgrenzen von Salzgesteinen und Salztektonik," *Kali, Verwandte Salze und Erdöl*, Vol. 30 (1936), pp. 191–94, 204–07, 214–17.
85. TAYLOR, M., "Shaft Sinking at Texas Salt Mine," *Mining and Metallurgy*, Vol. 11 (1930), pp. 580–83.
86. ———, "Shaft Sinking at the Morton Salt Company Mine at Grand Saline, Texas," *U. S. Bur. Mines Inf. Cir. 6640* (July, 1932). 9 pp.
87. TAYLOR, R. E., "Origin of the Cap Rock of Louisiana Salt Domes," *Louisiana Geol. Survey Bull. 11* (1938). 189 pp.
88. WEGMANN, C. E., "Über Diapirismus (besonders im Grundgebirge)," *C. R. Soc. Géol. de Finlande*, No. 3 (1930), pp. 1–19.
89. WILLIS, BAILEY, "Artesian Salt Formations," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 32 (1948), pp. 1227–64.

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VOL. 33, NO. 11 (NOVEMBER, 1949), PP. 1830-1858, 13 FIGS.

STRATIGRAPHY OF FRIO FORMATION ORANGE AND JEFFERSON COUNTIES, TEXAS[1]

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ABSTRACT

Recent development in the Gulf Coast of Texas has indicated the productive possibilities of many of the sands composing the lower part of the thick Frio formation of Oligocene age (considered to be Miocene by some workers). Exploration to the deeper sands of the Frio discloses facts of depositional conditions of this formation, which are as critical as structure for the accumulation of petroleum.

In Orange and Jefferson counties the Frio formation is divisible into three lithologic units: an upper unit consisting primarily of sands; a middle unit of marine shale; and a lower unit consisting of sands and shale. Isopach maps reveal the location of ancient offshore bars and re-entrant basins and also show local thinning of beds in areas of structural uplift. The variation in stratigraphic position of certain foraminiferal associations is believed to be due to ecological changes and to the marine progressive overlap.

INTRODUCTION

Orange and Jefferson counties, in the southeastern part of Texas Gulf Coastal Plain, is an area characterized by the gulfward-dipping homocline locally interrupted by salt domes, and faulted anticlines.

The area described includes most of Orange County and the northern part of Jefferson County (Fig. 1). The southwestern part of Jefferson County including the Fannett and East Fannett fields and Winnie-Stowell field is not considered here because it represents a separate structural area and depositional basin. Within the area under consideration, oil has been found associated with (1) salt domes: Orange, Port Neches, and Spindletop domes producing from sands of Miocene age, and from sands of the Anahuac and the Frio formations of Oligocene age (considered Miocene by some workers); (2) faulted anticlines: West Beaumont and Nome fields, producing from Anahuac and upper Frio, Amelia, and Lovell's Lake fields producing from upper and lower Frio, and North Vidor, North Cheek, South China, and Gilbert Ranch fields producing from lower Frio; and (3) stratigraphic traps: North Port Neches producing from the lower Frio.

The Frio formation, which occurs between the Anahuac and Vicksburg formations, normally consists of more than 2,500 feet of neritic and marine sands and shales. The sands have produced to date more than 30 million barrels of oil from the fields listed.

The subsurface problem has involved the study of more than 150 electrical

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logs, paleontological data and core records of wells drilled in the area. Those wells which penetrated beyond the top of the Frio formation and for which electrical logs were available are encircled in Figure 1. This study includes all wells drilled as of January 1, 1948, together with certain information from key wells more recently drilled.

The marine Frio formation in the Gulf Coast is known entirely from subsurface study, since its updip surface equivalent is an assemblage of non-marine sand and clay, possibly the same as the Catahoula formation.[3] To the writer's knowledge there is no published information on lithologic subdivisions of the Frio in the Texas Gulf Coast, and opinions differ widely on this subject.

The purpose of this work is, by the analysis of all available subsurface data on the Frio formation (1) to formulate a practical lithologic subdivision that will serve as a basis for structural interpretation, (2) to determine the extent of the sands that might be involved in stratigraphic traps, and (3) to define the position of microfaunal assemblages in the lithologic complex. No effort is made here to determine the precise geologic age of the Frio, or to correlate it with other formations. The Frio is generally considered as middle Oligocene in age,[4] but there is evidence to suggest that the age may be Miocene.[5]

STRATIGRAPHY

The term "Frio" as used in this report is the "subsurface Frio" as described by Deussen and Owen,[6] and Ellisor.[7] Long commercial usage has applied the term "Frio" to the sand series which underlies the Anahuac formation (upper Oligocene marine shale wedge) and overlies the Vicksburg formation.

The Anahuac formation[8] is recognized as that section predominantly shale, with calcareous and sand members, characterized by the occurrence of *Discorbis* species, *Heterostegina* species, and *Marginulina* species. It is commonly difficult to differentiate the lithologic character of the *Marginulina* zone, which consists of grayish green, brittle shale with thin- to massive-bedded fine-grained sands, from the Frio, which consists of green, waxy-textured shales with coarser-grained, frosted and more massively bedded sands. Thus, from electrical logs, this contact

[3] A. Deussen and K. D. Owen, "Correlation in Gulf Coast of Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 23, No. 11 (November, 1939), p. 1632.

[4] E. H. Sellards, "Stratigraphy of Texas," *Univ. Texas Bur. Econ. Geol. Bull. 3232*, pp. 700–10.
Alva C. Ellisor, "Anahuac Formation," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 28, No. 9 (September, 1944), pp. 1359, 1365.
D. W. Gravell and M. A. Hanna, "Subsurface Tertiary Zones of Correlation," *ibid.*, Vol. 22, No. 8 (August, 1938), pp. 984–1013.
———, "The *Lepidocyclina Texana* Horizon in the *Heterostegina* Zone, Upper Oligocene, of Texas and Louisiana," *Jour. Paleontology*, Vol. 11, No. 6 (September, 1937), pp. 520–22.

[5] James A. Waters, "Stratigraphy and Paleogeography of the Catahoula-Frio Formation," read before the Association at Denver, April, 1948.

[6] A. Deussen and K. D. Owen, *op. cit.*, pp. 1603–34.

[7] Alva C. Ellisor, *op. cit.*, pp. 1355–75.

[8] Alva C. Ellisor, *op. cit.*

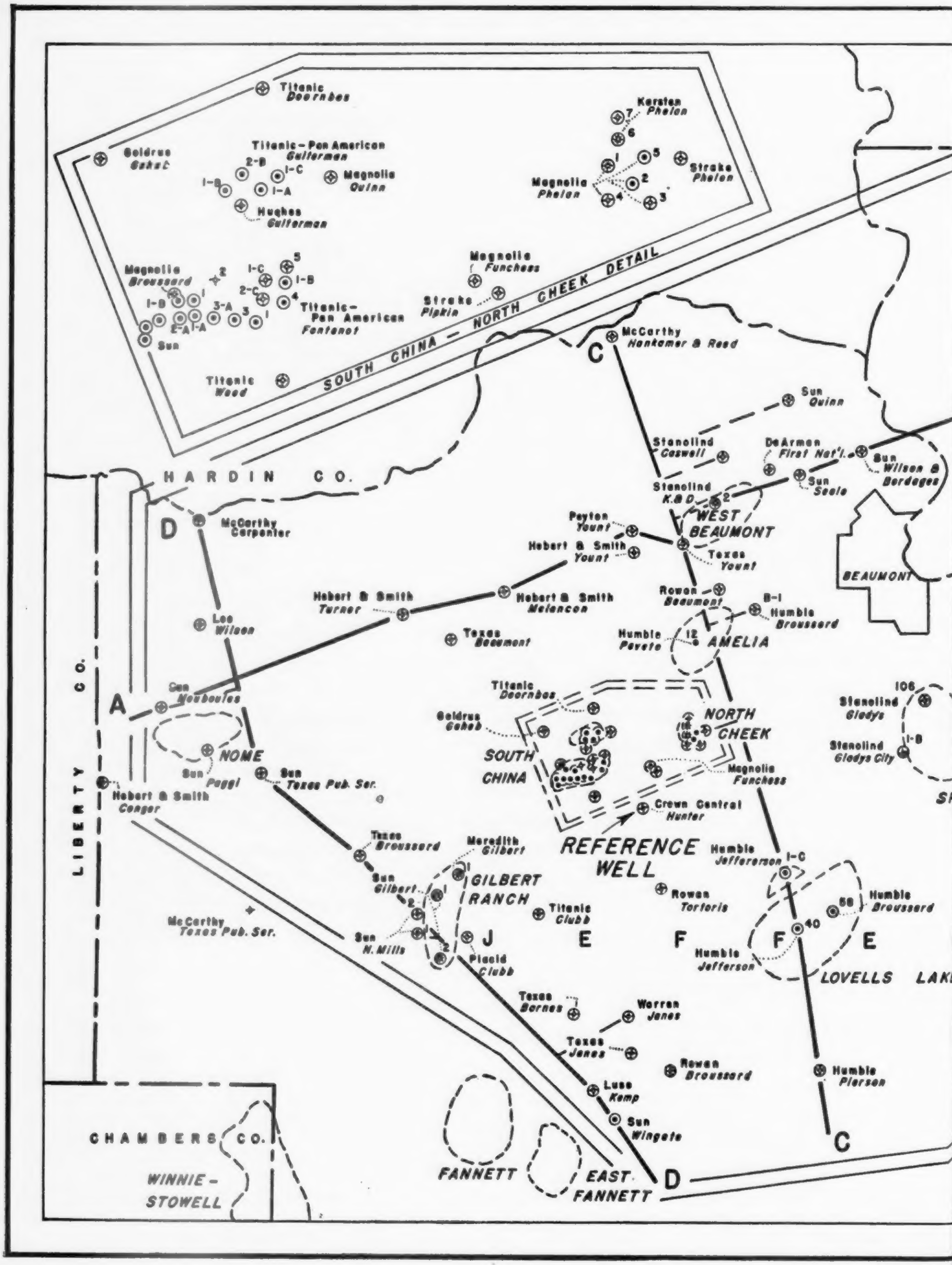
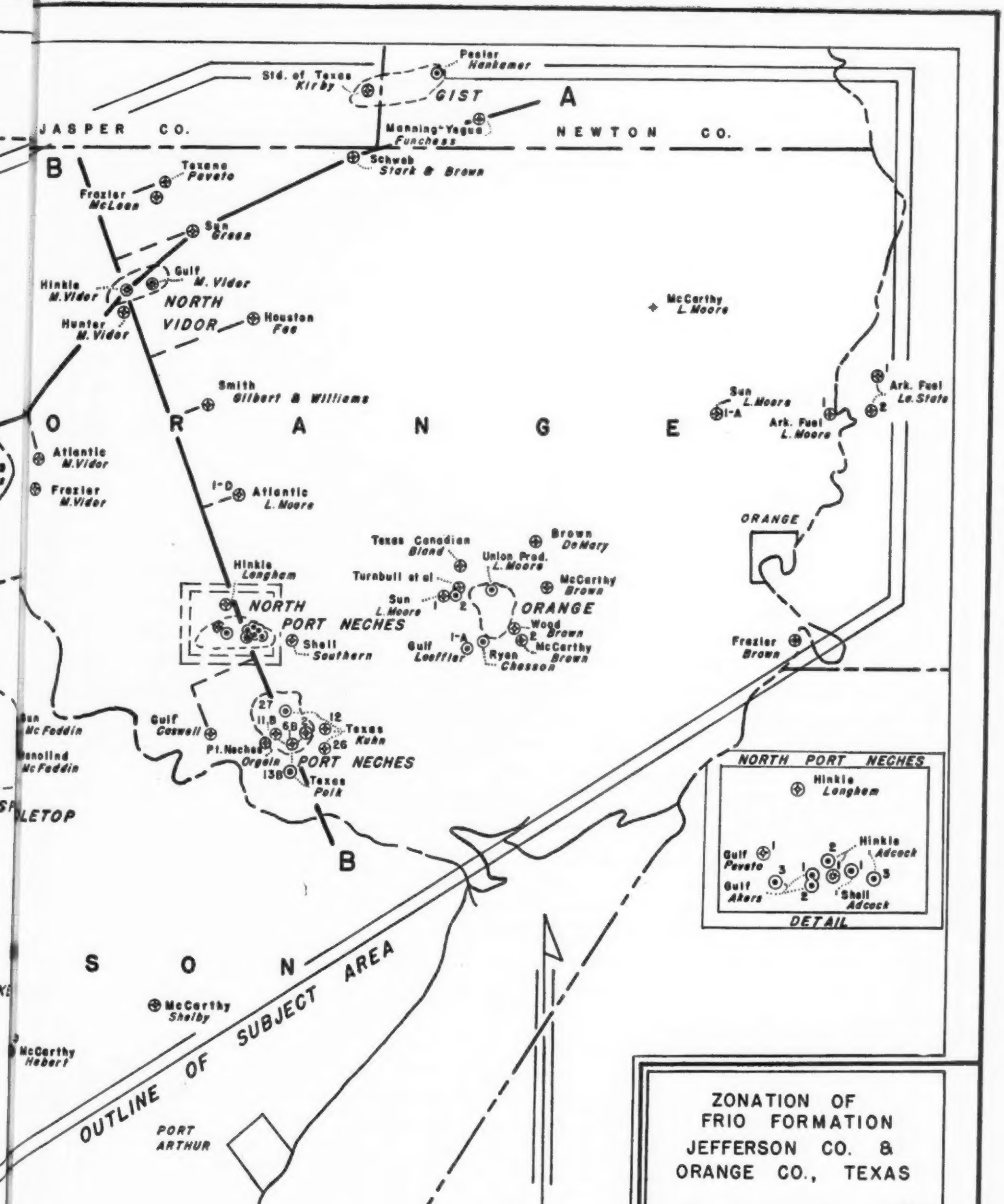


FIG. 1.—Index map, indicating locations of wells drilled below top of Fri[illegible]ormat[illegible]



f Fri ormation as of January 1, 1948. Wells encircled had electrical logs available.

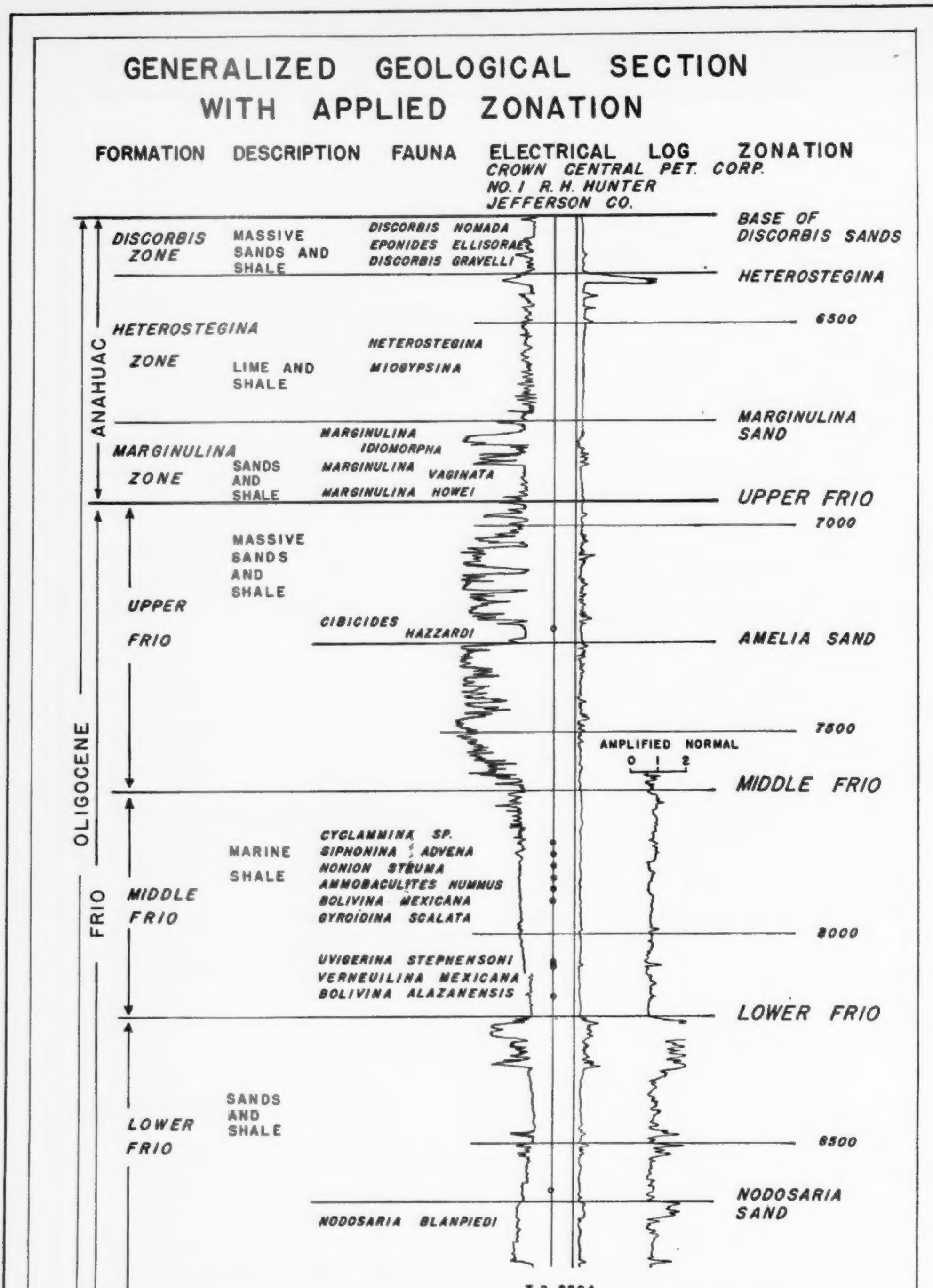


FIG. 2.—Reference well with applied zonation of Frio formation. Occurrence of paleontological fauna indicated as found in well.

between the *Marginulina* sands of the Anahuac formation and the sands of the Frio formation is variable and subject to the individual's interpretation.

The deposition of the Anahuac formation suggests a period of subsidence[9] during which the sea advanced far inland, depositing the marine shales and the reef limestone. The *Marginulina* sands were developed as the strand-line transgressed and the *Discorbis* sands were developed as the seas retreated.

Like the Anahuac, the Vicksburg formation was formed during a period of subsidence,[10] when the strand line advanced farthest inland. These deposits are characteristically marine shale and contain the foraminifer, *Textularia warreni* Cushman and Ellisor.[11]

The Frio was formed during a period of partial emergence, between the retreat of late Vicksburg and the advance of early Anahuac time. There were additional oscillations of the sea during middle Frio time, most marked of which was the advance of the sea forming the marine middle Frio shale wedge.

Figure 2 is a generalized geological section, which shows the three Frio members as recognized on a typical electrical log. This log should be considered for reference and does not represent a type log, because of the rapid transitional nature of the Frio formation. The paleontological markers are shown as actually found in this well and do not indicate their regional occurrence. This electrical log is interesting because it illustrates also the reaction of the self-potential curve to contamination in the hole due to a gas- and salt-water flow. A sand was encountered while drilling from 8,790 to 8,800 feet, which flowed gas and salt water. This flow was killed and the electrical log run to 8,804 feet. The self-potential curve from depths of 8,500–8,800 feet indicates less sensitivity due to the salt content of the mud in the hole, which decreased the normal potential change between sand and shale. The self-potential curve was so masked that it does not indicate the characteristic normal curve of the sand which was logged and side-wall cored from depths of 8,650–8,690 feet. However, this sand can be identified on the amplified normal curve. This phenomenon has been observed in many electrical logs, particularly in the middle and lower Frio zones.

UPPER FRIO

This zone of characteristically massive-bedded sands (from 6,950 to 7,653 feet in reference log, Fig. 2) of neritic to marine facies was deposited by marine progressive onlap. It decreases from a thickness of 1,100 feet updip to 200 feet downdip, and has a distinctive species, *Cibicides hazzardi* Ellis. Updip, this foraminifer occurs generally near the base of the upper Frio, rising in the section downdip until it occurs near the top of the Amelia sand member (Langham sand of the Amelia field), and in the extreme downdip section, this species occurs

[9] A. Deussen and K. D. Owen, *op. cit.*, p. 1620.

[10] A. Deussen and K. D. Owen, *op. cit.*, p. 1619.

[11] Alva C. Ellisor, "Jackson Group of Formations in Texas with Notes on Frio and Vicksburg," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 11 (November, 1939), pp. 1321–22.

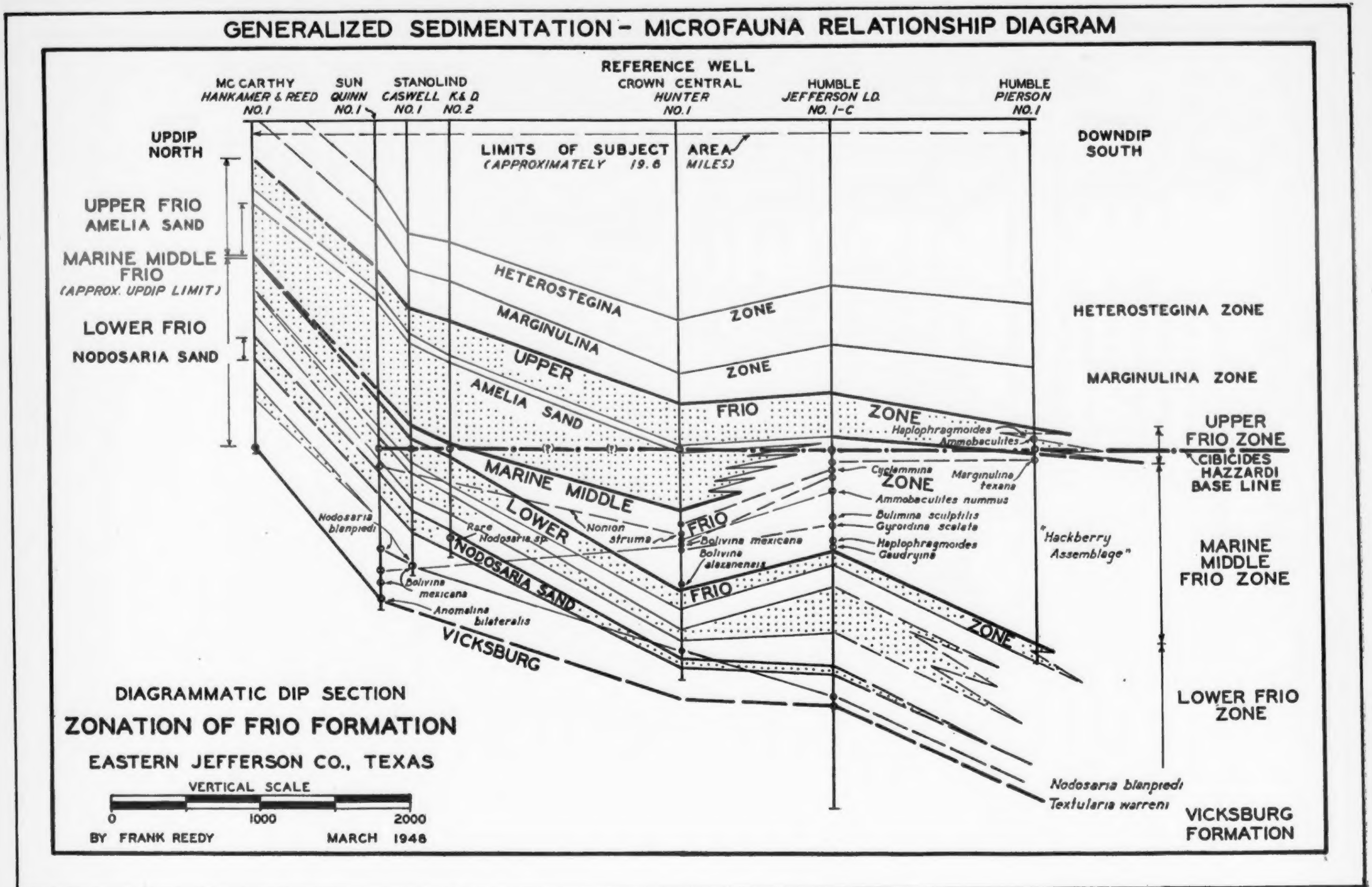


FIG. 3.—Diagrammatic dip section showing transgression of the zones of Frio formation from updip facies to downdip facies. Vertical relationship of wells based on occurrence of *Cibicides hazzardi* Ellis.

near the top of the upper Frio zone (Fig. 3). The massive character of these sands diminishes downdip as the shale content increases.

The Amelia sand[12] is a massive sand midway in the upper Frio zone easily recognized on the electrical log (as from 7,290 to 7,653 feet in the reference log, Fig. 2), which is distinctive of the lower part of this zone. The basal part of the Amelia sand member suggests interbedded thin sand and shale (as from 7,500 to 7,630 feet on the reference electrical log, Fig. 2). In Jefferson County the Amelia sand grades into shale downdip between the Amelia and Lovell's Lake fields.

MARINE MIDDLE FRIO

This marine shale wedge (as indicated from depths 7,653–8,199 feet in reference log, Fig. 2) representing the shale phase of deposition of transgressive-regressive seas, varies in thickness from 100 to 1,300 feet downdip. This shale member has a very rich faunal association including the following.

Cyclammina sp.
Haplophragmoides sp.
Siphonina advena Cushman
Ammobaculites nummus Garrett
Bolivina mexicana Cushman
Gyroidina scalata Garrett
Uvigerina stephensoni Garrett
Marginulina texana Garrett and Ellis
Verneuilina mexicana Nuttall
Bolivina alazanensis Cushman
Nonion struma Ellis

These species among those described as the "Hackberry assemblage" by J. B. Garrett,[13] become abundant generally as far updip as the 400-foot isopach interval of the middle Frio. Farther updip occurrence of this faunal association is limited by the ecological condition of deposition. The individual species occur updip near the base of the middle Frio, rising downdip to the base of the upper Frio zone (Fig. 3).

LOWER FRIO

This is a marine sand and shale sequence below the middle Frio shale (indicated in reference log at 8,199 feet, Fig. 2), and above the Vicksburg formation. Updip this zone consists of four sand members with alternating shale. Downdip the individual sands pass into shales (Fig. 3). In the vicinity of the reference well, the lower Frio zone generally consists of three sand members, as on the reference log, 8,199–8,320, 8,470–8,535, and 8,650–8,690 feet. The first sand of the lower Frio is the productive sand, locally known as the "Guiterman" or "Fontenot" sand in the South China field. This first sand is also the productive sand in the North Port Neches field. The third sand is commonly marked by the occurrence of the foraminifer, *Nodosaria blanpiedi* Ellis, although in Orange County adult representatives of the species actually occur below the sand.

[12] Ed J. Hamner, "Amelia Oil Field," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 23, No. 11 (November, 1939), p. 1652.

[13] J. B. Garrett, "Hackberry Assemblage—An Interesting Foraminiferal Fauna of Post-Vicksburg Age from Deep Wells in the Gulf Coast," *Jour. Paleon.*, Vol. 12, No. 4 (July, 1938), pp. 309–17.

FIG. 3.—Diagrammatic dip section showing transgression of the zones of Frio formation from updip facies to downdip facies. Vertical relationship of wells based on occurrence of *Cibicides hazzardi* Ellis.

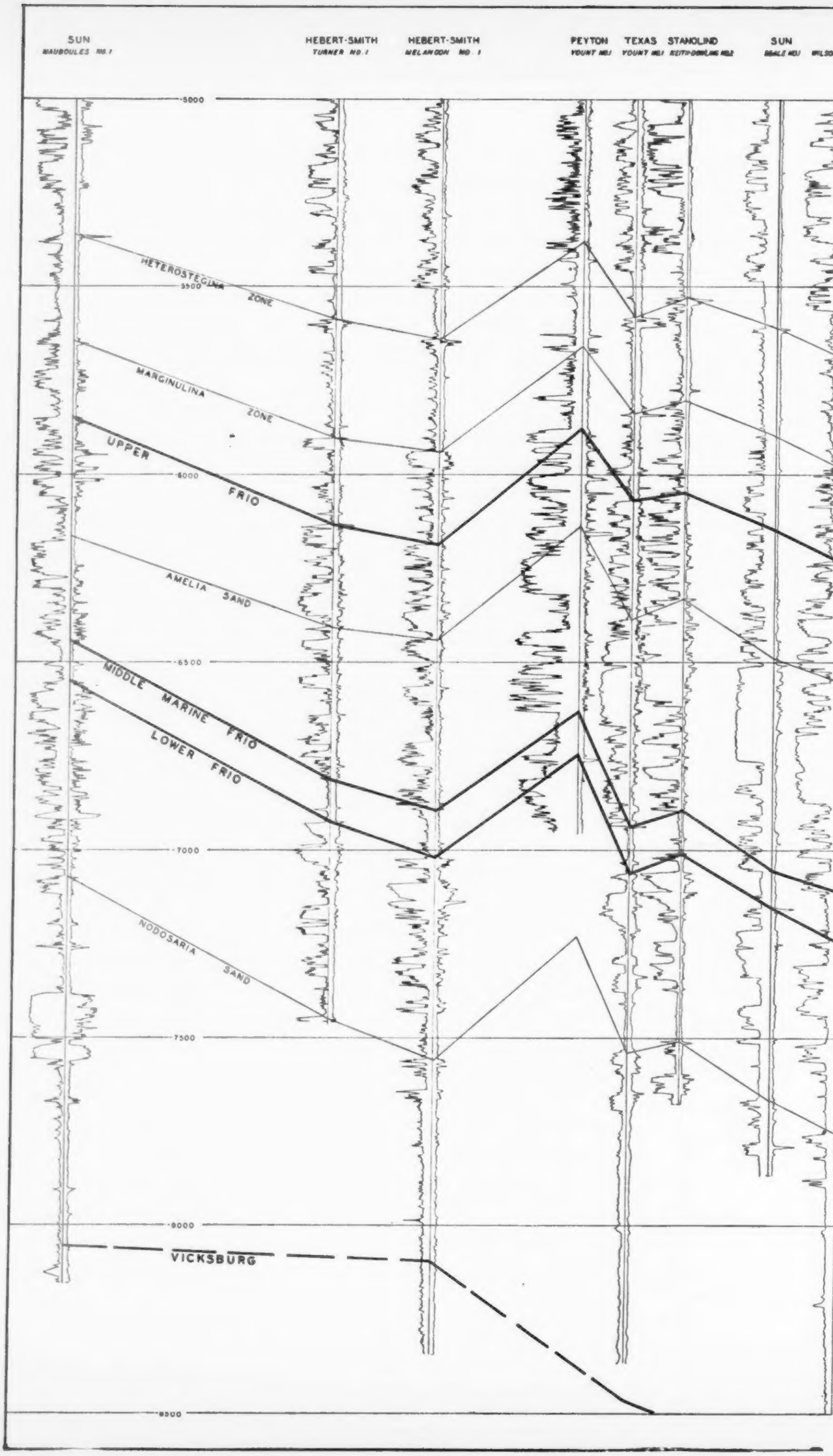


FIG. 4.—Strike section *AA* across Jefferson and Orange counties

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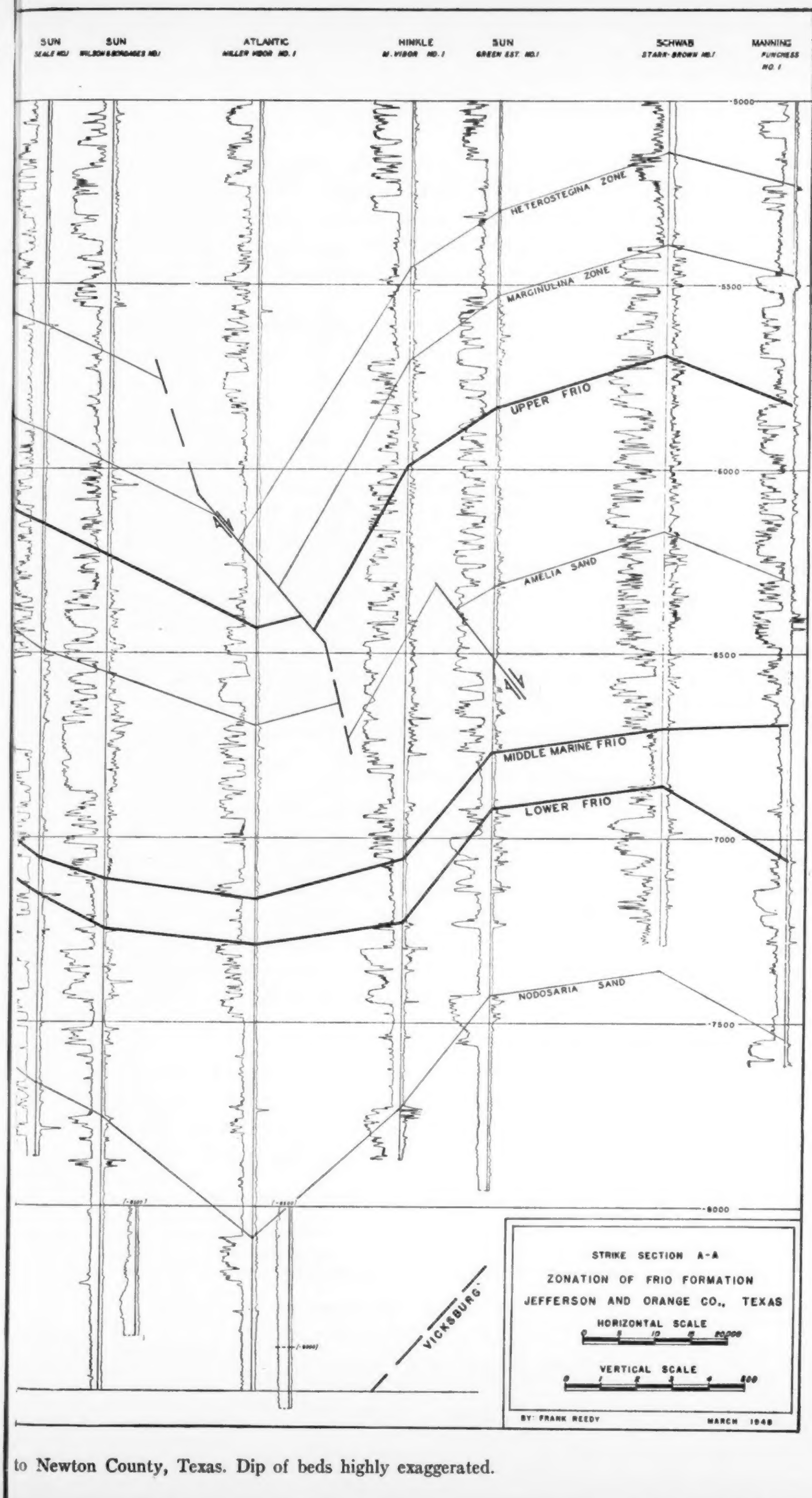


to Newton County, Texas. Dip of beds highly exaggerated.

There are exceptions to this general subdivision of the lower Frio zone, such as the following: Titanic's Fontenot No. 1-C, Strake's Pipkin No. 1, and Strake's Phelan No. 1, all in Jefferson County. These wells seem to exhibit evidence of subaqueous gliding[14] wherein the three sands generally found are consolidated into an over-all thin interval of this zone. This situation seems to be limited to a small area on the flank of structures.

Below the sands of the lower Frio is a thick shale section which has been completely explored by only a few wells in the district. Thus the data at hand are insufficient to define the nature of the Frio-Vicksburg contact.

SECTIONS

The location of the sections, as indicated on the index map, was designed to give the greatest coverage and the maximum use of available well control. Section *AA* (Fig. 4), composed of wells approximately on strike, is located along the line of flexure. Three dip sections, *BB, CC, DD* (Figs. 5, 6, 7), each uses a well in common with the strike section. These are drawn to show the change in a lithologic character of the zones both updip and downdip from the strike section. All of these electrical-log sections have a high degree of exaggeration of dip because a short vertical range of great detail was desired over wide linear distance. Strike section *AA* is drawn on horizontal subsea-level depth datum, while the dip sections, due to the high exaggeration of the dip of the beds, have been constructed as stratigraphic sections drawn on the *Heterostegina* zone datum.

STRIKE SECTION AA (FIG. 4)

This section extends from the Nome field, Jefferson County, northeastward including wells of the West Beaumont and North Vidor fields, across Orange County to Newton County. This section indicates the uniformity and linear distance along strike which this subdivision of the Frio might be applied. The massive sands of the upper Frio are readily apparent. The marine middle Frio zone is consistently uniform. The lower Frio consists of sands and shales with the *Nodosaria* sand as a correlative horizon. The Atlantic Refining Company's Miller Vidor No. 1 is actually downdip from the true line of strike.

DIP SECTION BB (FIG. 5)

This dip section extends from the north line of Orange County south to the Port Neches dome. The Gulf Oil Corporation's Caswell Trust No. 1, on the west flank of the dome, is projected into the section according to its structural position on the top of the upper Frio. North and updip from the Hinkle Drilling

[14] Subaqueous gliding may be defined as the local slumping of unconsolidated marine sediments down a dipping slope such that minor interformational unconformities might occur at the base of the slope. In the wells mentioned, the loss of the two thin shale members between the three sands of the lower Frio might be described as the depositional unconformity due to this gliding. See also

R. W. Fairbridge, "Submarine Slumping and Location of Oil Bodies," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 30, No. 1 (January, 1946), pp. 84–92.

A. W. Grabau, *Principles of Stratigraphy* (1924), pp. 660, 780.

W. H. Twenhofel, *Principles of Sedimentation*, p. 530.

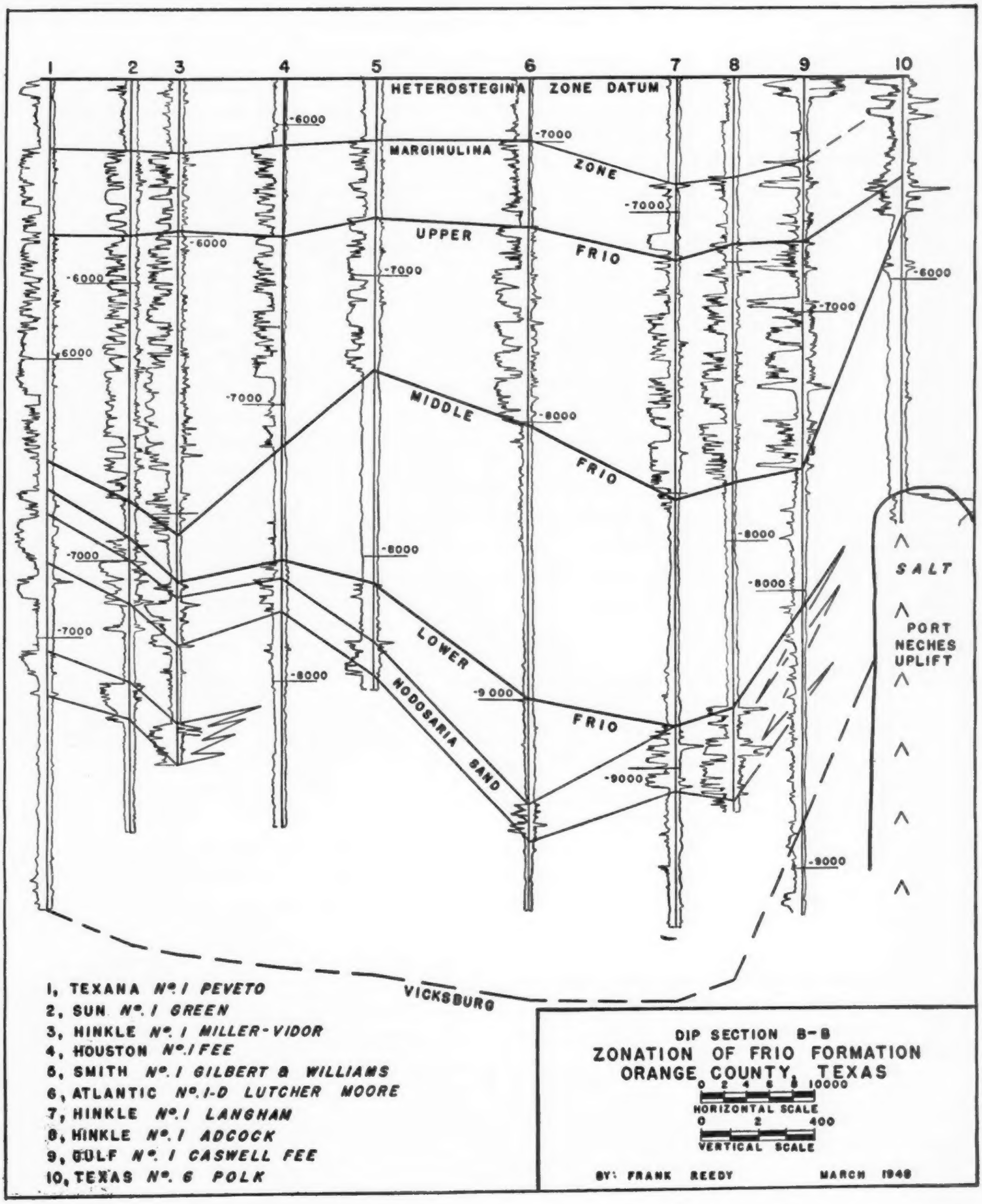


FIG. 5.—Dip section *BB* from north to south across western Orange County. Gulf Oil Corporation's Caswell Trust No. 1 electrical log is projected into line of section according to its structural position on top of Frio. Hinkle Drilling Company's Miller Vidor No. 1 is discovery well of North Vidor field and Adcock No. 1 is discovery well of North Port Neches field.

Company's Miller Vidor No. 1, the *Marginulina* fauna of the Anahuac formation is not fully developed; thus, the contact between the *Marginulina* sands and the upper Frio sands is questionable; therefore, the top of the upper Frio is based on electrical-log correlations.

The upper Frio zone with its massive sands thins in projection downdip, decreasing toward the axis of the embayment, and then thins abruptly on the north flank of the Port Neches dome. The Texas Company's Orange National Bank No. 5 (not shown in the section), on top of the dome, had no sands in the Frio, going from the Miocene sands into the middle Frio shale.

The marine middle Frio, characteristically a marine shale wedge, thickens downdip into the embayment, and then thins on the north flank of the dome, combining with the shales of the lower Frio and the Vicksburg to form a sheath covering the dome.

The lower Frio zone as projected downdip decreases its sand content to the axis of the embayment as indicated in the Atlantic's Lutcher-Moore No. 1-D. The *Nodosaria* sand as correlated represents a distinctive horizon which merges with the first sand of the lower Frio on the north flank of the dome. As indicated by the Gulf Oil Corporations Caswell Trust No. 1, this sand pinches out on the flank of the dome. The wedging of this lower Frio sand accounts for production in the North Port Neches field.

DIP SECTION CC (FIG. 6)

This dip section extends from the north line of Jefferson County south, including a deep test in the West Beaumont field, an east outpost of the Amelia field, the discovery well of North Cheek field, two deep tests of Lovell's Lake field, and a downdip wildcat well. The updip wells showing the massive character of the sands have limited fauna; therefore, correlations are based on interval and electrical-log characteristics.

The upper Frio sands, as a whole, thin perceptibly downdip, but this loss in section is mainly due to the transition of Amelia sand into shale. The Humble Oil and Refining Company's Pierson No. 1 indicates the feather edge along the downdip limit of the upper Frio sands.

The marine middle Frio wedge is hardly apparent in the McCarthy's Hankamer and Reed No. 1 and thickens gradually downdip, increasing to 1,300 feet.

The lower Frio contains thick massive sands with thin shales updip which, when projected downdip, separate into three distinct sands. The Magnolia Petroleum Company's Phelan No. 1 encountered a gas and salt-water flow (alike to reference log, Fig. 2), which no doubt reduced the sensitivity of the self-potential curve, thus obscuring the presence of sands in the lower Frio.

DIP SECTION DD (FIG. 7)

This dip section extends from the north line of Jefferson County south to the Nome field, southeast through the Gilbert Ranch field to include deep downdip wildcats.

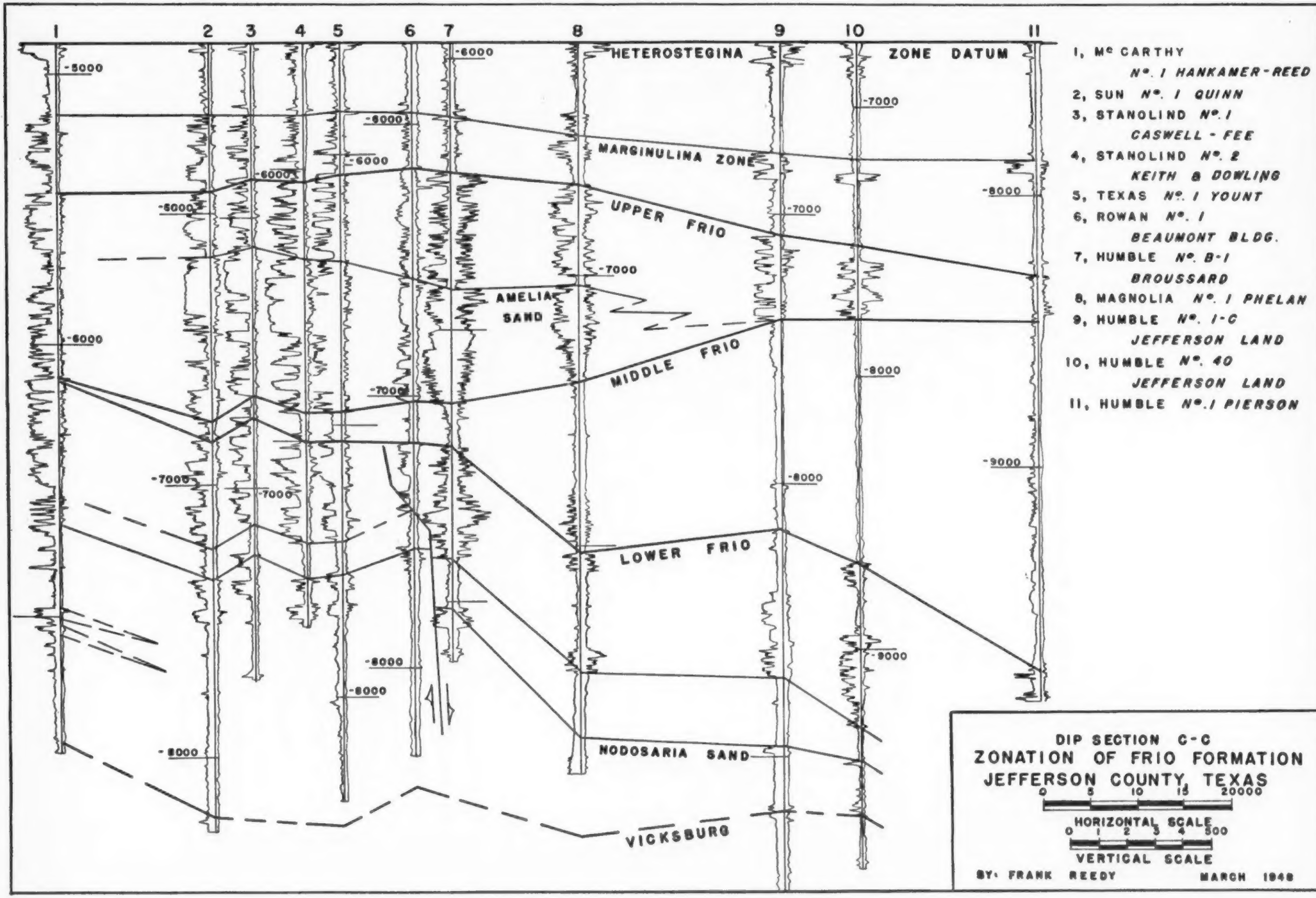


FIG. 6.—Dip section *CC* from north to south through eastern Jefferson County.

The upper Frio contains massively bedded sands which thin abruptly southeast of the Gilbert Ranch field. The Amelia sand is indistinguishable from the other massive sands of the upper Frio, and the *Cibicides hazzardi* where present occurs below the upper Frio sands.

The middle Frio wedge consists of 100–200 feet of shale from its updip trace downdip to the Gilbert Ranch field (as indicated by the Sun Oil Company's Nona Mills No. 1 of the electrical-log section *DD*), downdip from which the shale wedge thickens abruptly to 1,120 feet.

In the updip position of this section, the lower Frio zone contains nearshore maximum sand development, and the Sun Oil Company's Nona Mills No. 1 has a section like the reference log (Fig. 2). It is not believed that the Warren Petroleum Company's Janes No. 1 reached the sands of the lower Frio zone. The Sun Oil Company's Wingate No. 1 indicates the downdip limit of the sands of this zone.

ISOPACHS

To determine the practical application of the classification here described isopach maps of individual zones have been drawn. The isopach interval was computed from the electrical log of each well, as circled on the respective isopach map. Where faulting was observed to intersect two wells in different zones, the amount of displacement was added to each zone. Where a zone appeared to be less than normal in thickness, and no displaced section could be identified, this difference was interpreted as stratigraphic variation.

UPPER FRIO (FIG. 8)

In general, the upper Frio zone indicates a thinning downdip from 1,100 feet to less than 200 feet in thickness. This general pattern is interrupted in the presence of salt domes by a thinning on the flanks and crest of the dome.

In central Orange County there is evidence of a deep re-entrant on the updip sides of Orange and Port Neches domes. In this area the thickness of the upper Frio zone decreases toward the axis of the re-entrant. The intradomal areas suggest great thickness of the zone. This is illustrated in the Shell Petroleum Company's Southern Production Company No. 1, which encountered more than 1,000 feet of upper Frio zone as compared with less than 900 feet of like interval in the wells in the North Port Neches field.

A striking feature in northern Orange County is the apparent development of an offshore bar, trending northeast and southwest, including the North Vidor and Gist areas. There are not sufficient data at present to establish the amount and extent of the thinning updip beyond this apparent bar.

In Jefferson County, it is not evident that the isolated steep bar and re-entrant are present, but rather that a wide flat bar exists. Significant variations occur on the south flank of this bar, as noted in the abrupt local thinning on the Lovell's Lake, Gilbert Ranch, and Fannett structures.

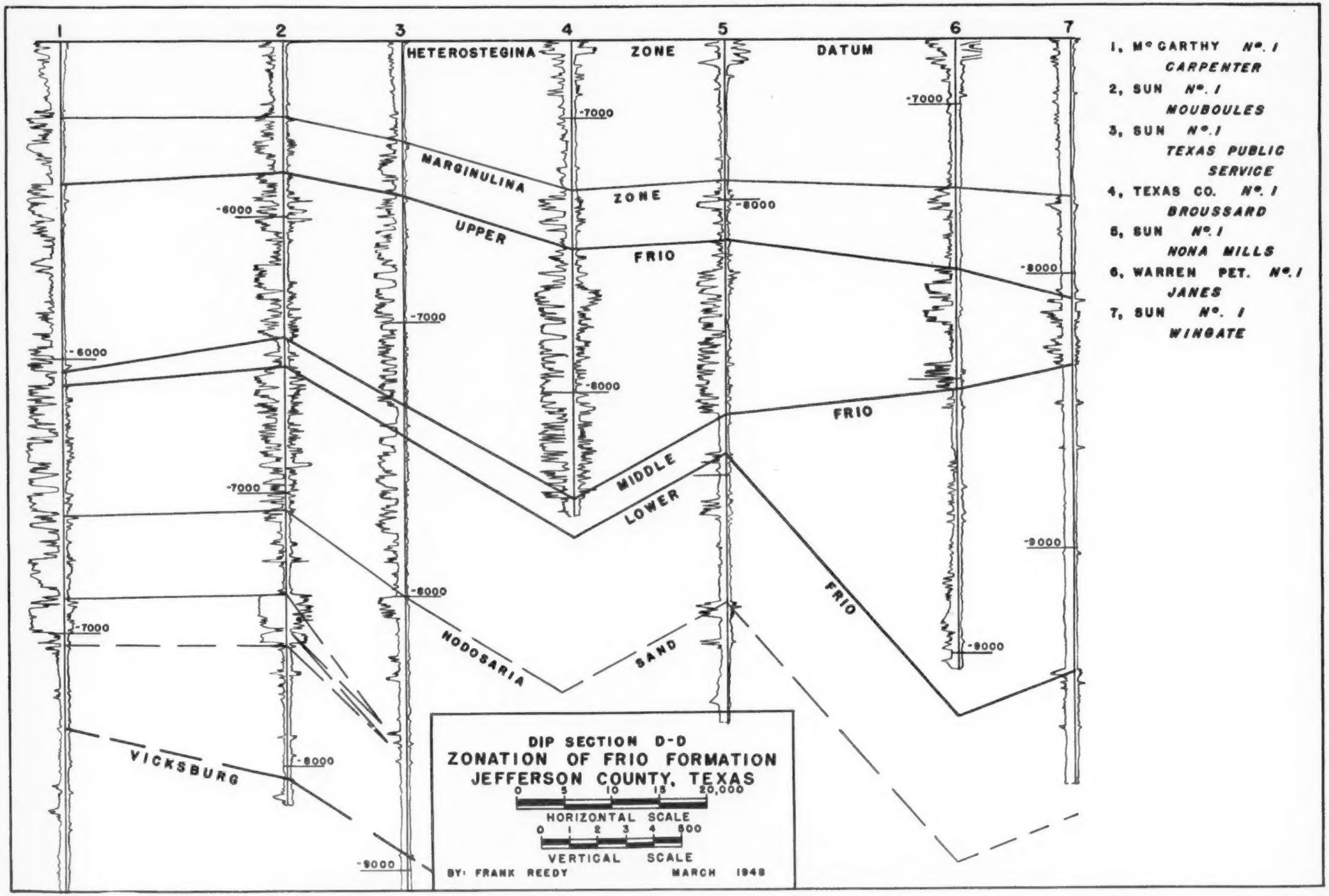


FIG. 7.—Dip section *DD* from northwest to southeast through western Jefferson County.

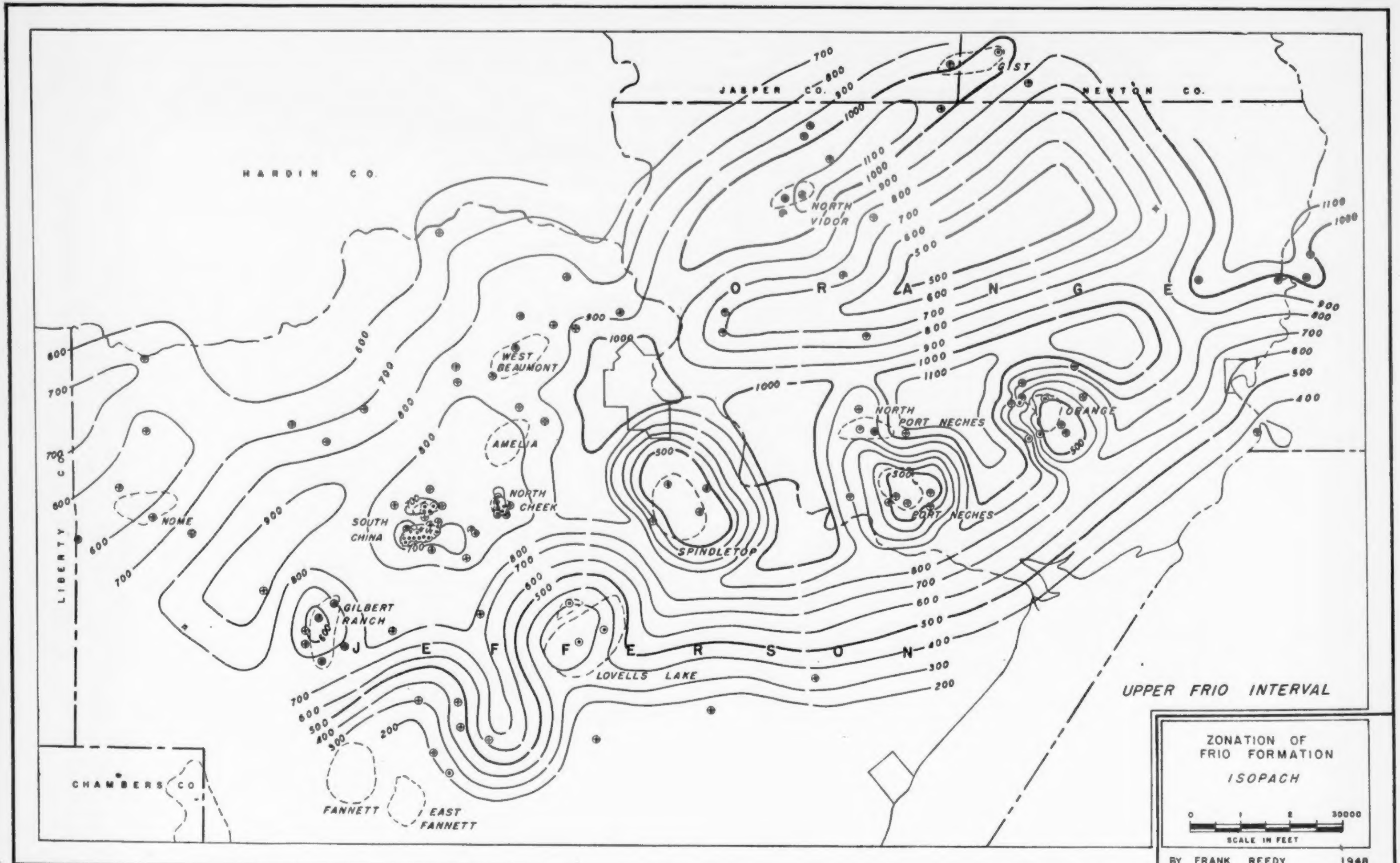


FIG. 8.—Isopach map of upper Frio interval. Wells encircled penetrated this zone.

FIG. 8.—Isopach map of upper Frio interval. Wells encircled penetrated this zone.

MIDDLE FRIO (FIG. 9)

This map of the middle Frio shale wedge shows a thickening from less than 100 feet to greater than 1,300 feet downdip. North and updip from the trend of Amelia, North Vidor, and Gist structures, the interval is very erratic and variable, indicating the crest of the flexure, while downdip from this trend the interval increases in a short distance.

In Orange County, the re-entrant is again observed on the updip side of Orange and Port Neches domes. In this re-entrant the middle Frio zone reaches its great thickness, thinning as it rises on the north flanks of the domes. Here also the intradomal areas are suggestive of great thickness.

In Jefferson County, the structures of Spindletop, Lovell's Lake, and Gilbert Ranch indicate distinctive thinning of the normal interval. In the South China field, there are two areas of production; the "Guiterman" at the north and the "Fontenot" at the south, both producing from the first sand of the lower Frio zone. In this field, it is interesting to observe the variations in the thickness of the middle Frio zone. In the "Guiterman" area, this zone in the producing wells vary from 205 to 283 feet in thickness, thus enclosed by a 300-foot isopach interval. A dry hole between the "Guiterman" area and the "Fontenot" at the south has an interval of 313 feet. In the "Fontenot" area, the producing wells vary from 440 to 510 feet in this interval. Adjoining dry holes have an interval in excess of 500 feet to as much as 614 feet. The highest structural wells in each area also seem to have the thinnest interval in the marine middle Frio zone. It is possible that these two areas are separated by a normal fault downthrown toward the south, which was accompanied by submarine slumping which might also account for the abnormal, compressed, constricted lower Frio zone in the Titanic's Fontenot No. 1-C.

UPPER AND MIDDLE FRIO TOTAL INTERVAL (FIG. 10)

This is a composite of the total interval from the top of the upper Frio to the top of the lower Frio. This over-all interval of the two separate zones indicates in general a thickening from 700 feet to approximately 2,000 feet downdip.

In Orange County, the outstanding feature is the re-entrant on the updip side of the salt domes. The North Port Neches area shows a definite nosing from the Port Neches dome.

In Jefferson County, the flat bar is still evident with the isopach interval thickening rapidly on the downdip flank. A re-entrant is again in evidence between Fannett and Lovell's Lake areas.

As few wells in this area have been drilled either to the Vicksburg formation or to the occurrence of *Textularia warreni*, there are insufficient data for the construction of an isopach map of the lower Frio zone.

PALEONTOLOGY

Diagrammatic dip sections have been constructed to integrate the available paleontological data with the lithology of the electrical log, to determine the re-

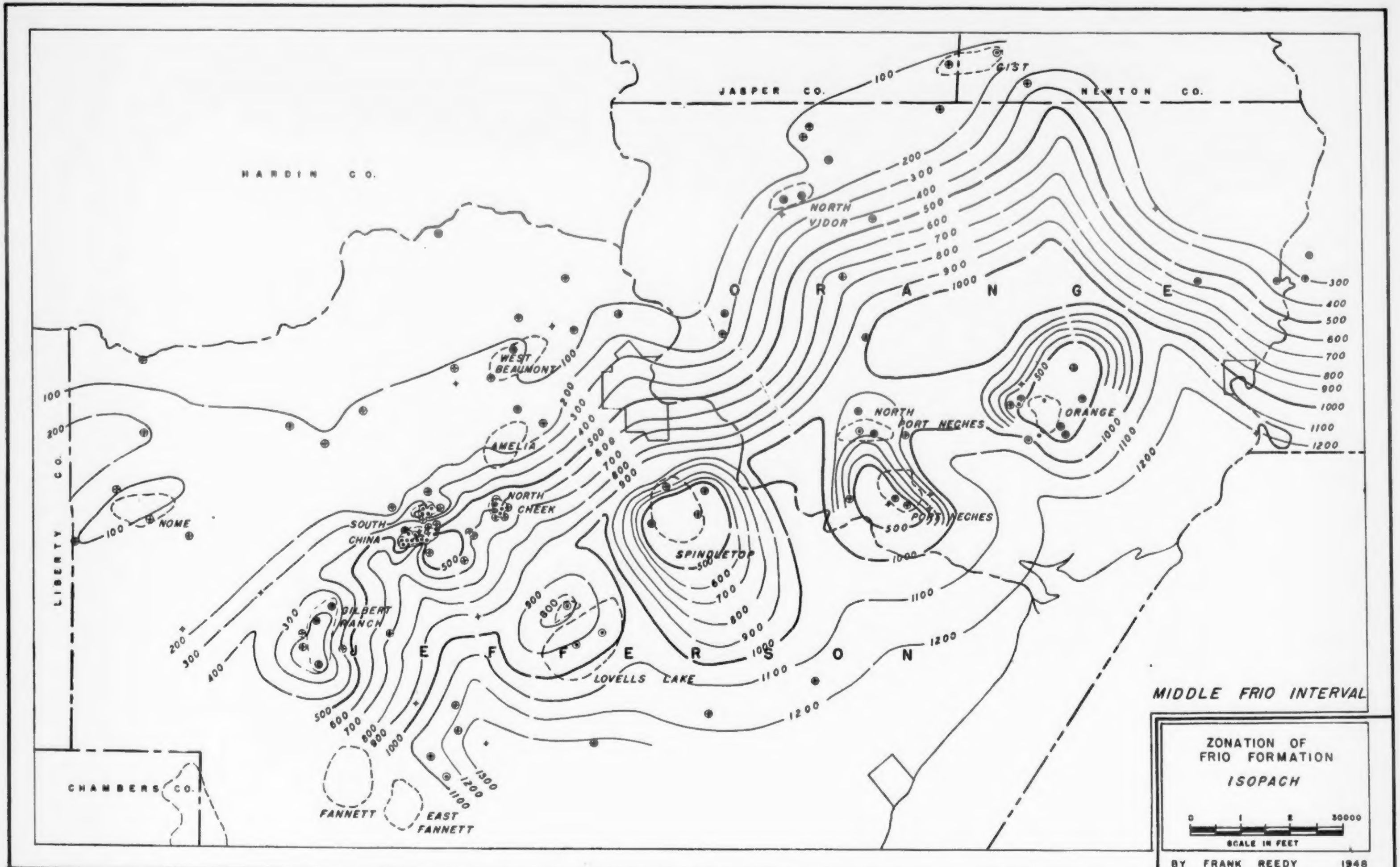


Fig. 9.—Isopach map of middle Frio interval. Wells encircled penetrated this zone.

FIG. 9.—Isopach map of middle Frio interval. Wells encircled penetrated this zone.

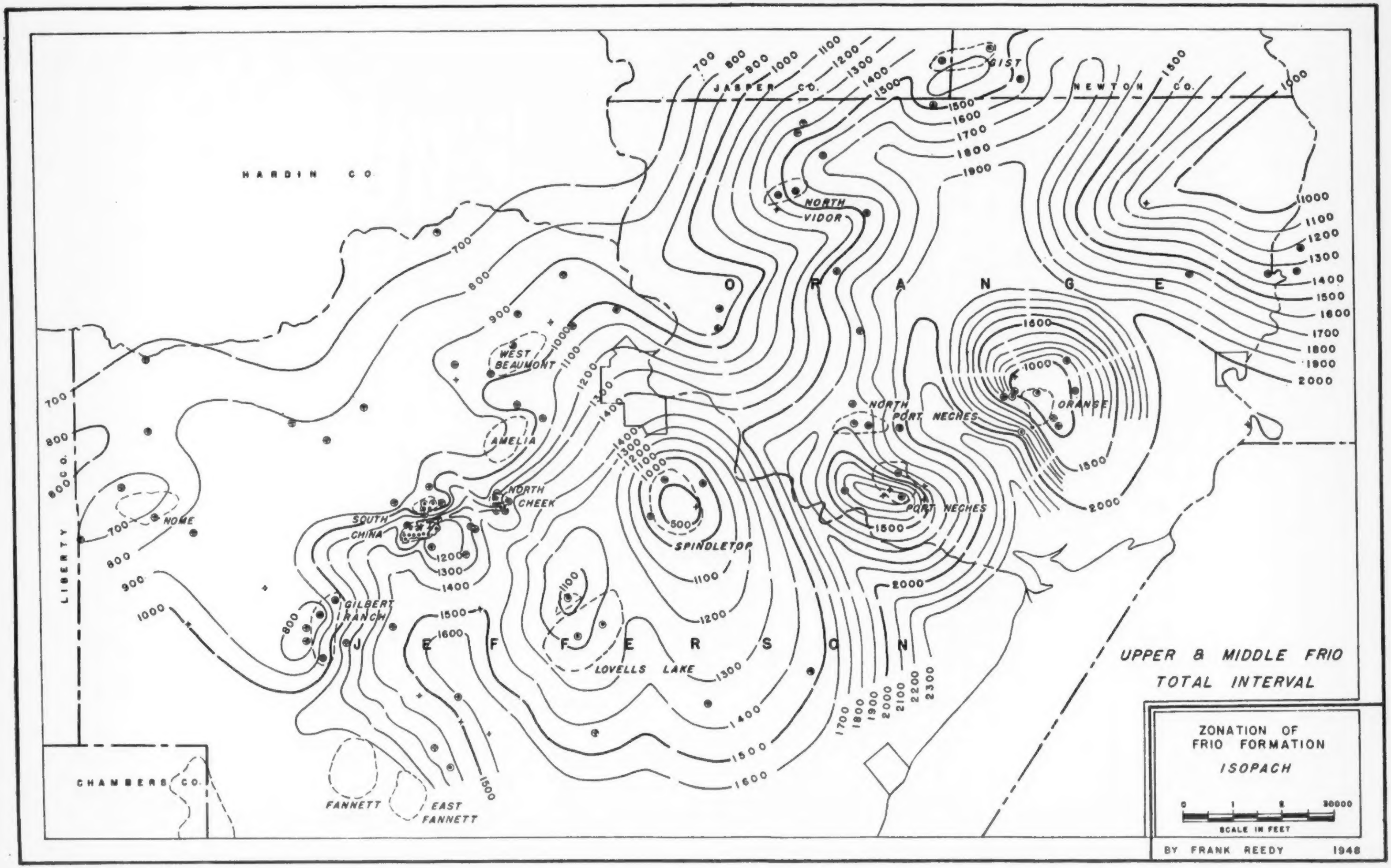


FIG. 10.—Isopach map of upper and middle Frio total interval. Composite of total interval from top of upper Frio to top of lower Frio, which is combined interval of Figure 8 and Figure 9.

lationship of the occurrence of foraminifera with the sand bodies, and to recognize those assemblages best suited for the purpose of correlation. The occurrence of the sands shown by stippling was taken directly from the electrical-log dip sections. By diagrammatic dip sections, it was possible to reduce the exaggeration of dip necessary in the construction of the electrical-log sections. The depth at which microfossils were found is indicated by a small circle at the well depth.

UPPER FRIO

Cibicides hazzardi is generally indicative of the upper Frio. This species from updip to downdip, transgresses from first occurrence in the marine middle Frio zone, rising nearly to the top of the Amelia sand in its type field, and ultimately nearly to the top of the upper Frio in its downdip limit.

MIDDLE FRIO

Downdip, this zone contains a very abundant and diagnostic fauna, described as the "Hackberry assemblage." *Cyclammina* and *Haplophragmoides* seem to extend farther updip into the neritic facies than the more typical marine forms of the Hackberry assemblage. It is not necessary to include here the entire list of Hackberry species, already so well described by J. B. Garrett.[15] Of this assemblage certain interesting observations can be made from a study of these sections: (1) two forms of *Ammobaculites* occur, with *Ammobaculites nummus* ranging as low as 500 feet below the upper species as in Smith and Gilbert's Williams No. 1, Orange County; (2) of these Hackberry species, the following seem to be the most widespread and abundant: *Gyroidina scalata, Marginulina texana, Bolivina mexicana, Nonion struma, Haplophragmoides,* and *Cyclammina.*

LOWER FRIO

In updip localities, the first occurrence of the *Nonion struma* is in the shale above the first sand of the lower Frio. But downdip, this species rises in the shale section with increasing interval to the first sand below.

Nodosaria blanpiedi is the most distinctive foraminifera of this zone, but it has caused confusion because it occurs in two varieties at different horizons. The upper form is a rare miniature variety, while the lower is the abundant typical adult form. In the Hinkle Drilling Company's Langham No. 1, Orange County, the interval between these forms is nearly 900 feet. The typical *Nodosaria blanpiedi* commonly occurs with or below the third sand of the lower Frio zone, herein called the *Nodosaria* sand.

PALEONTOLOGICAL ZONATION

The position of microfaunal assemblages in the lithologic complex is one of transitional trend as traced downdip. Regionally, the individual species can not be considered as diagnostic of a particular sand member. But locally, the occur-

[15] J. B. Garrett, *op. cit.*

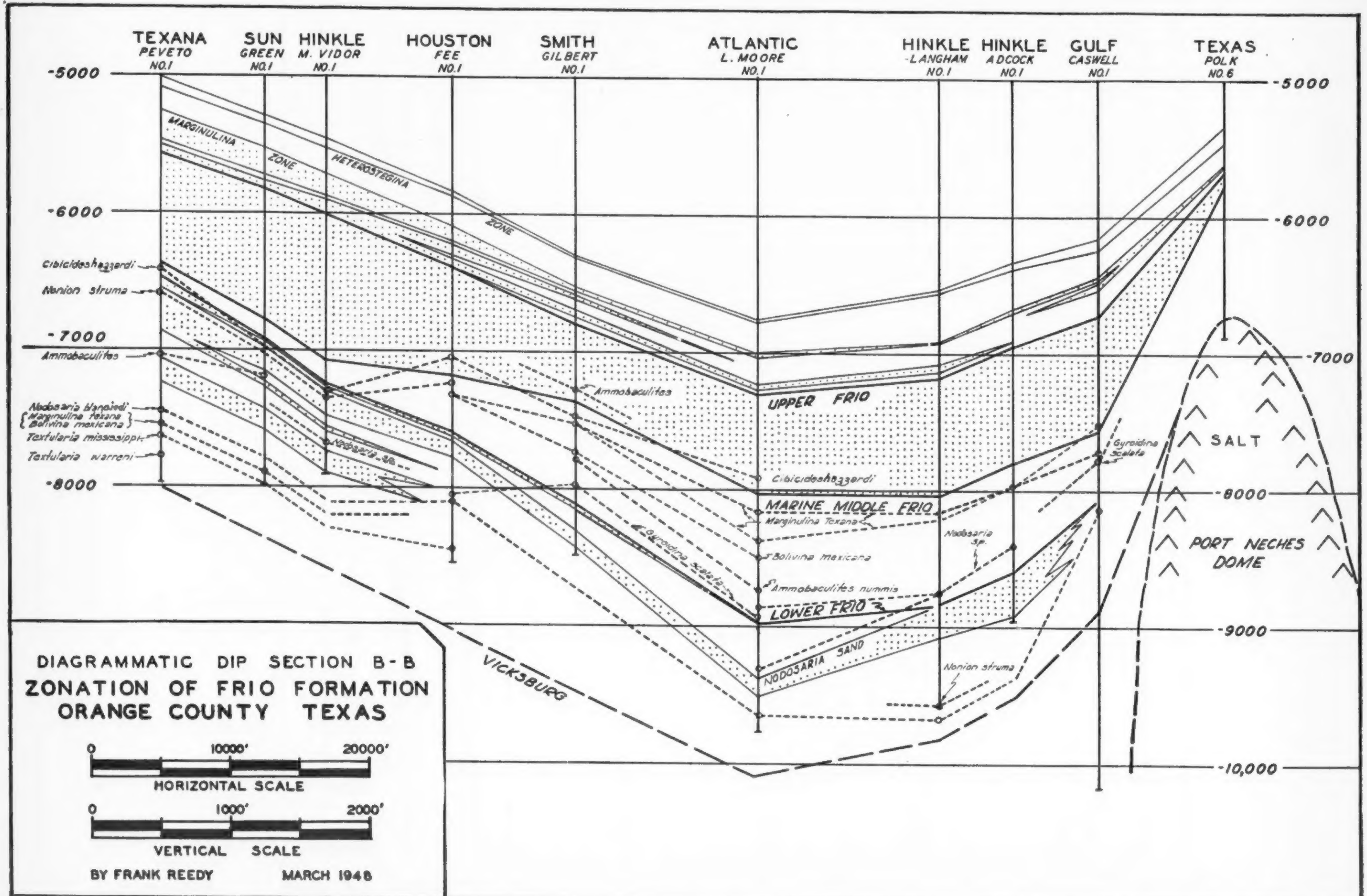


FIG. 11.—Diagrammatic dip section *BB*. Sand zones (stippling) taken from electrical logs of Figure 5.

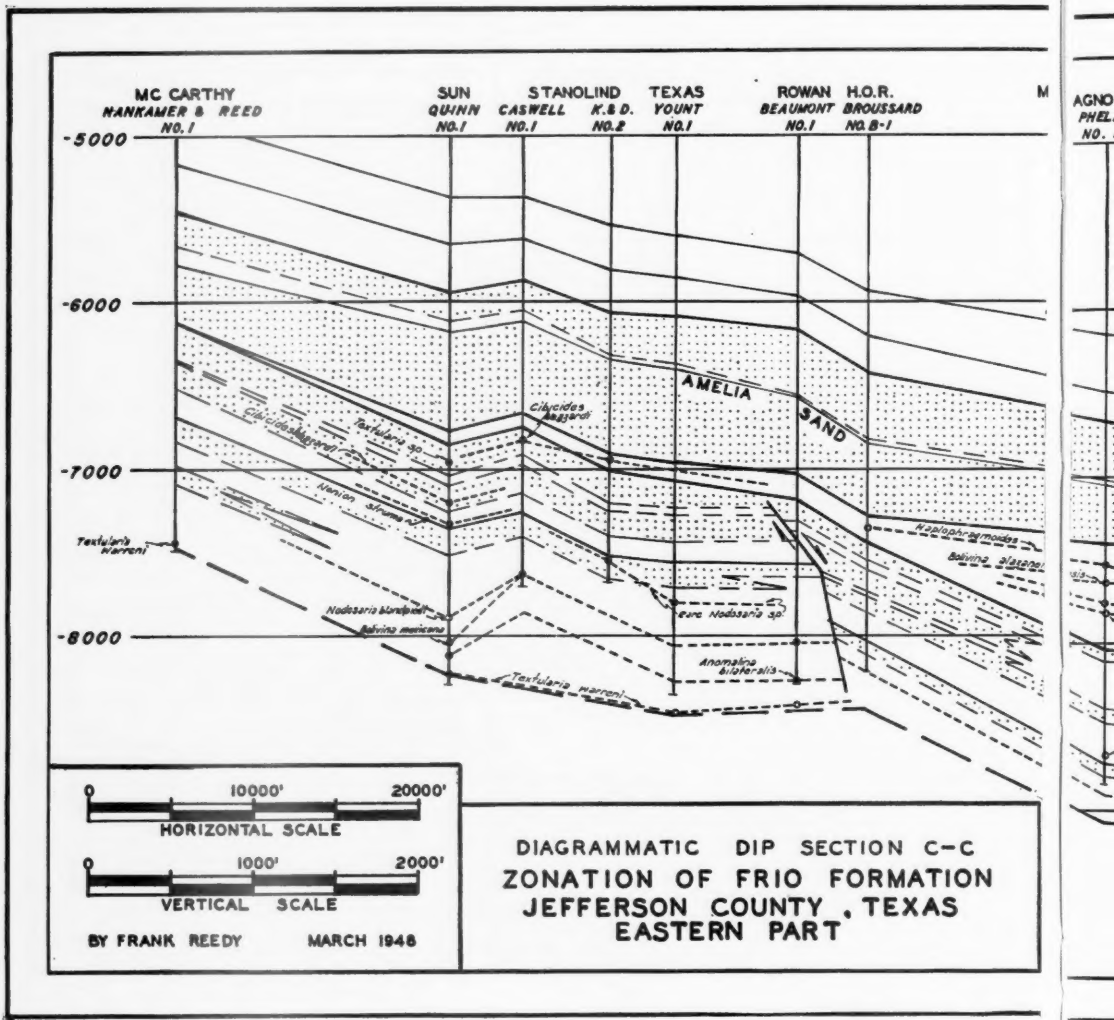
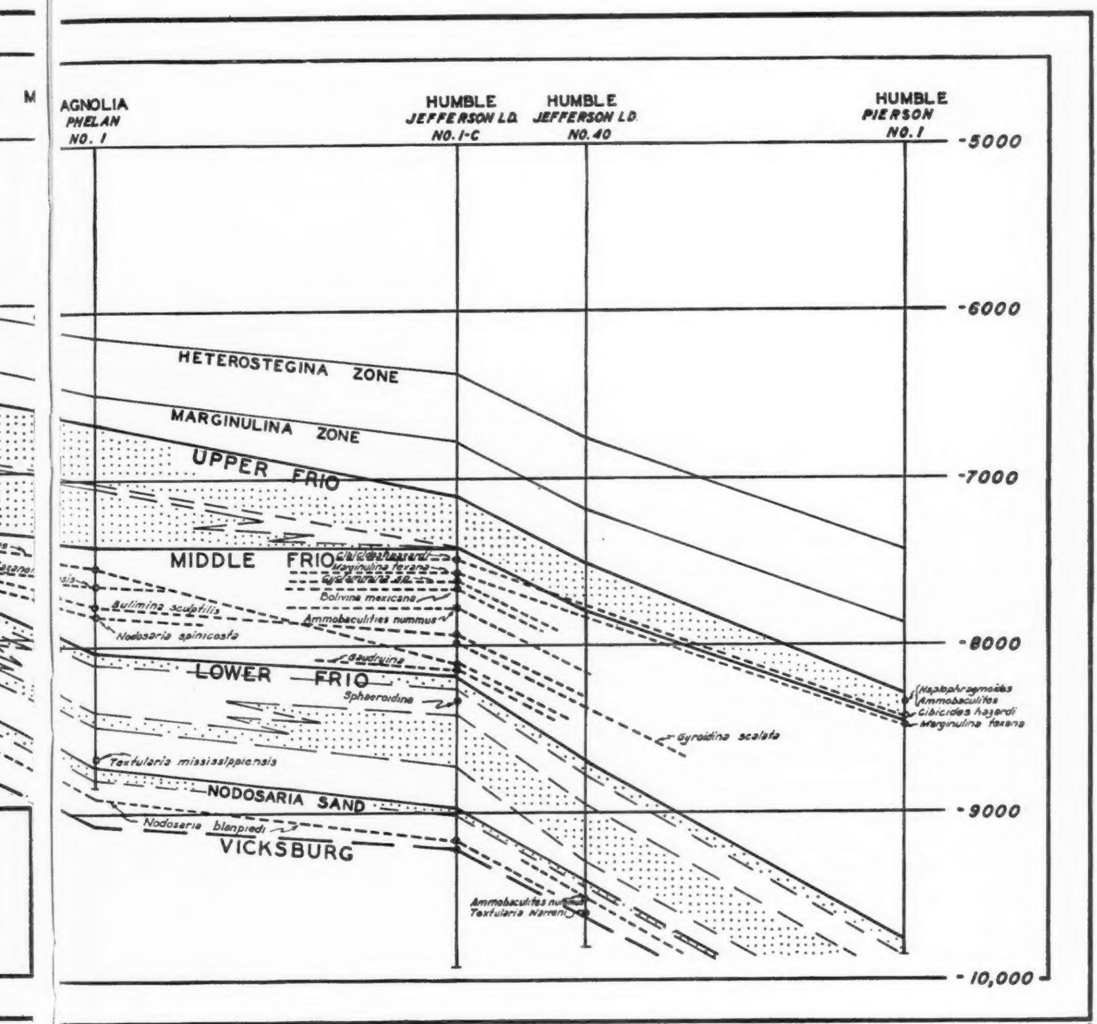


FIG. 12.—Diagrammatic dip section *CC*. Sand zones (stip



es (stippling) taken from electrical logs of Figure 6.

rence of microfauna might be recognized as indicative of a correlative lithologic unit.

The transitional trend of microfaunal assemblages, traced from updip to downdip, progresses across lithologic units. This progression is from older to younger members of the section. As the sands were deposited by the regression and transgression of the seas, the sands actually become younger in age with the direction of movement of the seas. Therefore, as the occurrence of microfauna might be considered depicting a limited time interval, the resulting divergence between these fauna and lithologic horizons becomes apparent downdip.

Ecologically, the deposition of the massive sands updip limited the presence of the fauna, which become more abundant in the marine section downdip.

Examples of the transgression of microfauna across lithological zones, rising with divergent interval gulfward, as indicated in the diagrammatic sections, are the following.

Cibicides hazzardi (Sections *BB, CC*) (Figs. 11, 12)
Gyroidina scalata (Section *BB*) (Fig. 11)
Bolivina mexicana (Sections *BB, CC*) (Figs. 11, 12)
Marginulina texana (Sections *BB, CC*) (Figs. 11, 12)
Haplophragmoides sp. (Section *CC*) (Fig. 12)
Ammobaculites sp. (Section *DD*) (Fig. 13)

SEDIMENTATION-MICROFAUNA RELATIONSHIP

The transgression of microfaunas across lithologic units is a significant feature of the stratigraphy of the Frio. Figure 3 illustrates this feature. The diagrammatic dip section drawn from north to south through eastern Jefferson County, indicates the lithologic character from the electrical-log dip sections, the sequence of microfaunas from the diagrammatic dip sections, and the data from the reference well. The vertical position of these wells in this diagram is based on the occurrence of *Cibicides hazzardi*. If a horizontal line is assumed for the occurrence of the *Cibicides hazzardi*, which has a limited vertical range and a wide horizontal distribution, this plane represents a time or stratigraphic datum.

This diagram illustrates the complex lithologic character of the Frio formation. Updip (north) massive sands of the upper Frio merge with sands of the lower Frio, for the middle Frio has reached its approximate updip limit. This section has a limited fauna. Tracing these zones downdip, the marine middle Frio thickens in a short distance as the sands of the upper and lower Frio grade into shale. At the downdip limit of the area, nearly all the Frio formation is marine shale, with only remnants of the upper Frio and lower Frio sands remaining.

The occurrence of *Cibicides hazzardi* progresses successively from the second sand to the first sand of the lower Frio; to the middle Frio; to the top of the Amelia sand; and finally to the base of the upper Frio zone. Likewise, *Nonion struma* and *Bolivina mexicana* cross from the lower Frio into the middle Frio. Other species of the "Hackberry assemblage" seem to be restricted to marine shale of the middle Frio. Significantly, the *Nodosaria blanpiedi* maintains its relative position with respect to the top of the lithologic lower Frio zone.

It is questionable that the projected trace of *Cibicides hazzardi* would transgress directly across the thick massive Amelia sand, as indicated in the diagram, between the Stanolind Oil and Gas Company's Keith and Dowling No. 2 and the Crown Central's Hunter No. 1. As this foraminifer is generally found either in the shale above or the shale below the Amelia sand, it suggests that the actual occurrence of this foraminifer moves downdip and higher in the section around the downdip extremity of the Amelia sand.

PROGRESSIVE OVERLAP

Grabau,[16] describing the characteristics of regressive deposits, states:

> As each formation or bed passes shoreward into coarser clastic it is evident that the shore ends of all the formations deposited during the retreat will together constitute a stratum of sandstone or conglomerate which in age rises seaward, since in that direction it is progressively composed of the ends of higher and higher formations.
>
> Thus the sand ends of all the beds will be exposed at or just above sea-level, and constitute a continuous sand formation, which however, is not of the same age at any two points along a line transverse to the direction of the shore. Such a sand formation will, however, be mapped as a unit, and receive a formational name. If the basal portion of such a sand is fossiliferous, it will contain in a seaward direction the fossils of successive higher formations.

Malkin and Echols[17] have illustrated the application of compound features of regression and transgression, showing diagrammatically the trend of facies across time lines.

These compound features of marine sedimentation are evident in the history of Frio stratigraphy. The transitional occurrence of microfauna across lithologic units as traced downdip, suggests the direction of the movement of the seas and the relationship of the position of the shore line with the ecology of deposition. Thus as each of the lithologic units can be traced in detail, then each represents a constant ecology following the movement of the seas. *Nodosaria blanpiedi* marks the regressive sea after Vicksburg time; the "Hackberry assemblage" is distinctive of the transgressive middle Frio seas; *Cibicides hazzardi* marks the regressive sea after middle Frio; and finally the *Marginulina* fauna is associated with the transgressive sea following upper Frio time. The basal part of the lower Frio, particularly in the southern part of the area, is the same lithologically as the underlying Vicksburg and the overlying marine middle Frio. The upper part of the lower Frio, however, in most of the area contains abundant sands which were deposited during a condition of uniform shallow depth of water, and of sorting of the clastics which is intermediate in time between the regression of the deeper Vicksburg sea and the transgression again with deeper water through the area of the marine middle Frio seas. A similar condition took place after the deposition and regression of the marine middle Frio and the transgression of the Anahuac

[16] A. W. Grabau, "Principles of Stratigraphy," p. 734.

[17] Doris S. Malkin and Dorothy Jung Echols, "Marine Sedimentation and Oil Accumulation. II: Regressive Marine Offlap and Overlap-Offlap," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 32, No. 2 (February, 1948), p. 255.

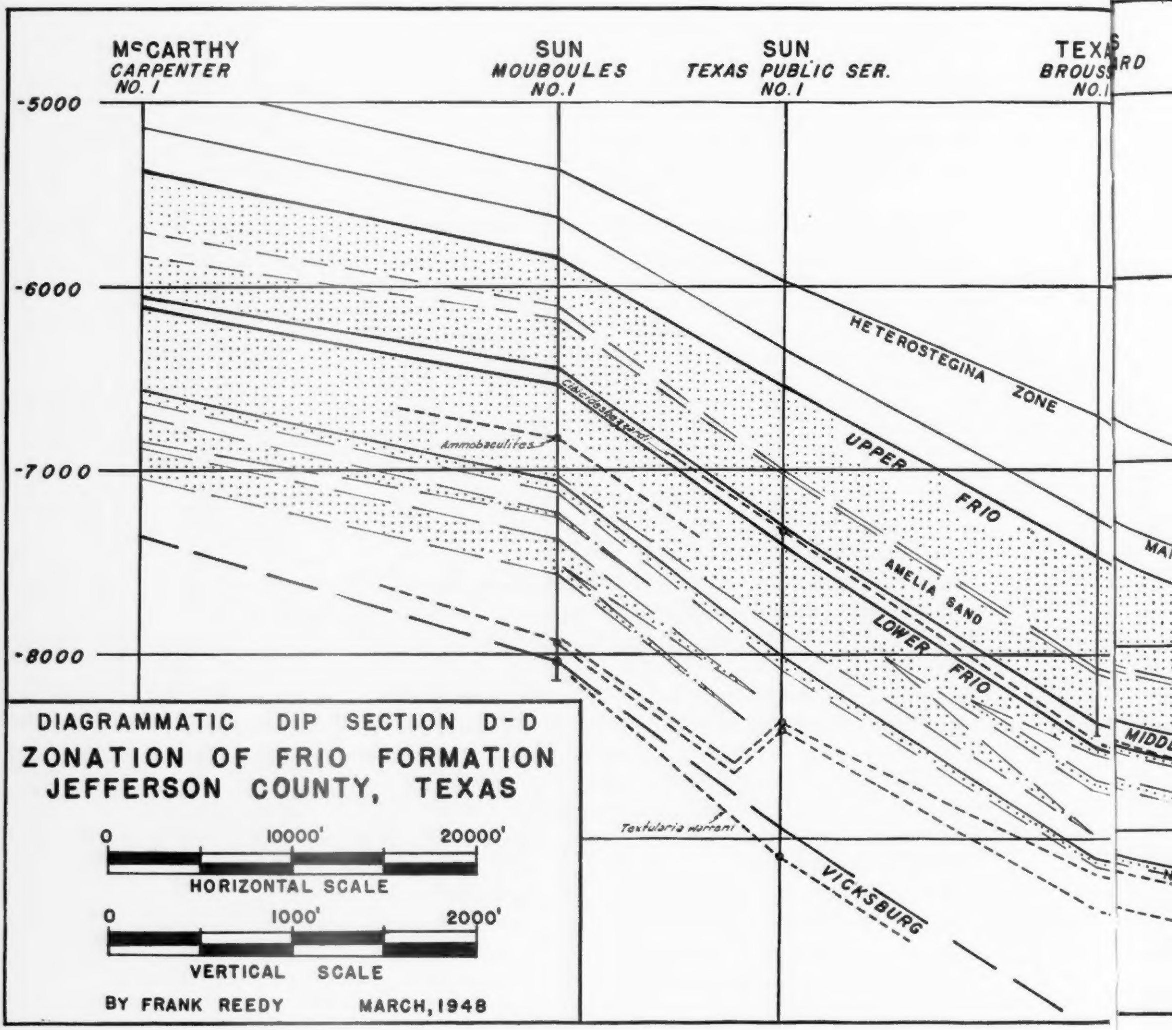


FIG. 13.—Diagrammatic dip section *DD*. Sand

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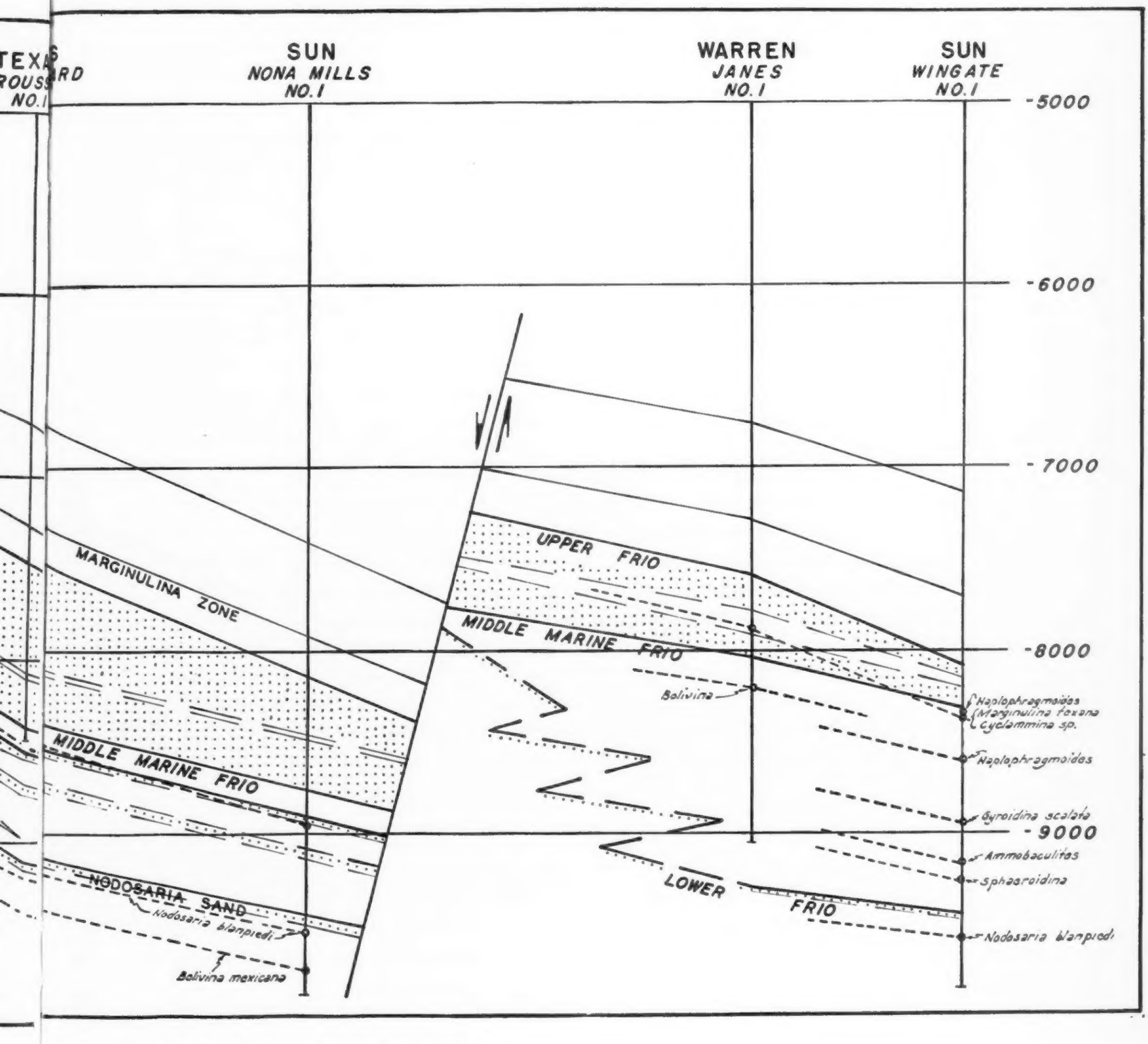

zones (stippling) taken from electrical logs of Figure 7.

seas, and in this latter interval the upper Frio was deposited throughout the area in the form of a series of sands, which condition was prevalent throughout the area excepting that there was very great thinning toward the southern end and over some of the piercement dome uplifts.

CONCLUSIONS

This study describes the stratigraphy of the Frio formation. The classification here presented applies only to the area involved, and as further work is done in adjoining areas, additional factors and variations will surely be recognized. In summary, the following results are enumerated.

1. Lithologically, the Frio can be subdivided into upper massive sands, middle shale wedge, and lower sands and shales.

2. The paleontological associations are *Cibicides hazzardi* with upper Frio, "Hackberry assemblage" developing in marine shale wedge, and *Nodosaria blanpiedi* associated with the sands of lower Frio.

3. Faunal occurrence, projected downdip, crosses lithologic zones and rises stratigraphically with transgressive sands and becomes lower stratigraphically with regressive sands.

4. Marine depositional environments are evident in each zone as the bar in upper Frio and re-entrants in middle Frio zones.

5. Local thinning of zones is apparent over structures.

6. Subdivision of Frio formation, as basis for structural interpretation, defines accurately the normal interval of each zone for fault determination.

7. Depositional factors of regressive-offlap and transgressive-onlap sands are recognized.

It is hoped that this study will stimulate further research in adjoining areas so that the complete stratigraphic history of the Frio formation may be known. Such a study will no doubt disclose additional stratigraphic and structural closures, which should be as prolific in the production of petroleum as those now producing.

BIBLIOGRAPHY

BECKELHYMER, R. L., "Stratigraphy of Waller and Harris Counties, Texas," *Bull. Amer. Assoc. Petrol. Geol.* Vol. 30, No. 1 (January, 1946), p. 58.

BORNHAUSER, MAX, "Marine Sedimentary Cycles of Tertiary in Mississippi Embayment and Central Gulf Coast Area," *ibid.*, Vol. 31, No. 4 (April, 1947), p. 701.

FAIRBRIDGE, R. W., "Submarine Slumping and Location of Oil Bodies," *ibid.*, Vol. 30, No. 1 (January, 1946), pp. 84–92.

ISRAELSKY, M. C., "Notes on the Frio," Report of Houston Geological Society Study Group, *ibid.*, Vol. 24, No. 2 (February, 1940), pp. 376–82.

KAY, MARSHALL, "Paleogeographic and Palinspastic Maps," *ibid.*, Vol. 29, No. 4 (April, 1945), p. 433.

KRUMBEIN, W. C., "Analysis of Sedimentation and Diagenesis," *ibid.*, Vol. 31, No. 1 (January, 1947), pp. 171, 174.

MALKIN, DORIS S., AND JUNG, DOROTHY A., "Marine Sedimentation and Oil Accumulation on Gulf Coast. I. Progressive Marine Overlap," *ibid.*, Vol. 25, No. 11 (November, 1941), pp. 2010–20.

MARTYN, P. H., AND SAMPLE, C. H., "Oligocene Stratigraphy of East White Point Field, San Patricio and Nueces Counties, Texas," *ibid.*, pp. 1967–2009.

STORM, L. W., "Résumé of Facts and Opinions on Sedimentation in Gulf Coast Region of Texas and Louisiana," *ibid.*, Vol. 29, No. 9 (September, 1945), pp. 1304–35.

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SEDIMENTARY TECTONICS AND SEDIMENTARY ENVIRONMENTS[1]

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ABSTRACT

The tectonic framework of sedimentation—basins, geosynclines, neutral areas, and positives—largely controls the distribution of sedimentary environments by its control of source areas, strand lines, and bathymetric zones. A major problem in distinguishing tectonic elements and tectonic intensity arises from the interplay between contemporaneous depositional subsidence, and intermittent uplift and erosion; and a major problem in evaluating environmental control arises from the time factor in the passage of sedimentary particles through the depositional interface. These problems and possible solutions are discussed in terms of a hypothetical cycle of deposition, in which tectonism, environment, and biological agencies are integrated in terms of their effects on the accumulation of sediments.

As a practical means of interpreting and designating the distribution of environments during a stratigraphic interval, a tectono-environmental classification is proposed, which includes groups of associated environments placed within a framework of increasing tectonic intensity. It is seen that the environmental impress on the sediments diminishes as a function of increasing tectonic intensity.

INTRODUCTION

Concepts of sedimentary tectonics and sedimentary environments are important both in academic and applied fields of geology, because of their significance in the interpretation of sedimentary characteristics. The parallel growth of these subjects, plus advances in conventional stratigraphic analysis, and in understanding of the tectonic framework of sedimentation, has shown that sediments respond to a variety of controls; but it has also raised questions involving the relative importance of the several factors in the composite picture.

In part, diversity of opinion arises from differences in the method of approach, and in part, from differences in the stratigraphic units or geographic areas studied. The concept of the sedimentary environment as an important agent in controlling sedimentary properties arose largely from the study of recent sediments, where the relation between geologic agents and sedimentary properties can be investigated. Sedimentary tectonics, on the other hand, developed from a study of ancient sediments, and stemmed from the observation that geosynclines have not only thicker deposits than the continental interior, but they differ from them also in their gross lithological characteristics.

The observable response of sedimentary characteristics, especially of ancient sandstones, to contemporaneous tectonism, has led some workers to discount the environment as a mere ephemeral accompaniment to a more fundamental set of controls. The student of recent deposits, on the other hand, sees a veneer of sediments respond to chemical and physical conditions of the depositional site, and questions whether tectonism may not simply shift this environmental pattern through time and space. The stratigrapher, faced with the problem of

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carrying correlations over wide areas, must take account both of changing environments and contemporaneous tectonism. The oil geologist, in his study of local structures, must decide whether they are due to contemporaneous structural growth, or to intervals of deposition punctuated by warping and erosion. The solution of such problems also involves both depositional environments and tectonism.

The purpose of the present paper is to examine problems of tectonism and environment in the light of recent advances in the study of these subjects. The thesis is presented that sediments are a response to the simultaneous operation of several processes; and that criteria are available for evaluating any stratigraphic section in terms of the interplay among environment, contemporaneous tectonic activity, lithologic associations, and erosional intervals. In cases in which erosional intervals are minor, contemporary tectonism plays a leading part, but not always a dominating part.

Discussion of environment and tectonism must take into account the fact that whereas every sediment by definition was deposited in some kind of environment, it is not necessarily true that contemporary tectonic activity was always present. The latter must be demonstrated from available evidence, to eliminate instances of alternate deposition and local erosion, as well as the effects of buried topography. That subsidence is required for the accumulation of sediments was demonstrated by Barrell (1917); but such subsidence may be continuous or discontinuous, and which is true in any case must depend on the evidence.

CRITERIA FOR TECTONISM

Half a dozen features require consideration in the reconstruction of tectonic events. The stratigraphic unit selected for study must have a definable top and bottom, which may be chosen on the basis of limiting unconformities, faunal characteristics, or lithologic changes. The unit itself must be carefully examined for smaller hiatuses within the section, and if present, their magnitude evaluated in areal extent, and in terms of the vertical gap represented. The lithologic and faunal characteristics of the stratigraphic units require detailed examination as do their variations vertically and laterally within the unit. Finally, three features of the bounding surfaces of the stratigraphic unit must be evaluated, as Kay (1945) has emphasized. These are (1) the present form of the lower datum surface (present structural configuration); (2) the form of the lower datum as deposition progressed (contemporaneous subsidence); and (3) the surface of deposition during the accumulation of the stratigraphic unit (the bathymetric relations of the sea bottom).

Inasmuch as the important point of contemporaneous tectonism must be firmly established, Kay's three features may be considered first. With respect to the Pennsylvanian, for example, the present attitude of the base of the system (or of any selected part of it) shows some areas of synclinal downwarp, others of

anticlinal uplift, and still others of essentially horizontal position. Are the non-horizontal structural attitudes entirely a result of post-depositional warping? If not, how much of the present attitude may be attributed to subsidence or uplift contemporaneous with deposition? Closely related to this question is another: how much of the present observed variation in thickness of the deposits is due to greater accumulation in local areas during subsidence, and how much is due to differential compaction, or to stripping of upwarped portions?

Criteria are available for choosing among the alternatives, provided sufficient surface and subsurface data are at hand. An isopach map, combined with cross sections of the stratigraphic unit, discloses whether smaller units within the larger unit thicken and thin across the area. These changes in thickness may be due to erosional hiatuses, to original buried topography, or to contemporaneous tectonic activity.

Criteria have been developed which are helpful in locating hiatuses in the subsurface, and they have been described elsewhere (Krumbein, 1942). Not all are reliable as unquestioned evidence of non-conformable relations, however, because many of the features also occur in strictly conformable sequences. Many unconformities on the thin outcrop belt seem to vanish in the thickened subsurface sections. Simultaneously with the thickening, the faunas become transitional vertically.

Failure to recognize hiatuses in detailed subsurface studies leads to serious errors in interpretation. Under conditions of uniform sedimentation followed by local uplift and erosion, the cross section shows thinner intervals on structure, where parts of the deposit have been stripped away. The cross section therefore may show the same kind of relative thickening and thinning as is shown by a section developed under conditions of contemporaneous tectonism.

The presence of hills and valleys in the original topography may have a strong influence on the attitude and thickness of succeeding deposits. Many instances of such buried topographic effects have been described (Lee, 1943; Wilson, 1948). Sediments deposited over an irregular surface adjust themselves by developing initial dips on the slopes, and by filling the intervening valleys before the hills are buried. Hence, some sections show not only thinner sections on structure, but inclined strata along the sides, much like a folded anticline. In general the effect of the original topography diminishes upward, and theoretically, once the intervening valleys are filled, the depositional surface should be essentially horizontal, except for the effects of differential compaction. In cross section this would be indicated by an increase in steepness of the structure with depth.

Within the range of thicknesses affected by buried topography, the beds may all be strictly conformable, thus leading to cross sections similar to those produced by local contemporaneous tectonic activity. The identification of buried topographic features depends on a close analysis of detailed sections, and on a close analysis of textural and other features of the lowermost sediments in contact with the old surface. The recent reconstruction of buried topography by Wilson

(1948) illustrates the detail with which such phenomena may be examined.

The common occurrence of sand on structure, grading into shale on the flanks has led to the inference that much structural relief is produced by differential compaction of the shales after burial. If depositional conditions were such that sand accumulated on the tops of buried hills, with mud accumulating in the adjoining valleys, subsequent burial would result in the muds suffering more compaction than the sand. As a consequence, the original dip of the beds would be accentuated by differential compaction. Moreover, the process could theoretically continue through a considerable vertical section, as subsequent beds of mud become compacted on burial. Many of the local structures in the Mid-Continent area of Kansas and Oklahoma have been assigned to such causes by some writers. McCoy (1934) considered the evidence for differential compaction in the Mid-Continent, and concluded that its effect was relatively minor in many instances; and that the occurrence of thin sections on structure above uniform intervals could not be explained by a continuation of the process.

As subsurface data accumulate, it becomes increasingly clear that structural features may be developed by each of the processes described. There is abundant evidence for deposition over buried hills, and for local or regional warping and erosion after deposition, as well as for contemporaneous structural growth during deposition. Differential compaction as a cause of structures is generally considered a secondary feature, which may accentuate structural attitudes developed by other means.

In addition to thinned intervals on structure without observable hiatuses, some intervals are uniform in thickness over the structure, but display marked lithologic changes on structure. It is not uncommon to find clean sand at the crest, grading into shale on the flanks, but without significant change in thickness. Moreover, such occurrences are superposed through a succession thicker than that required for burial and obliteration of topographic effects. It is difficult to explain such occurrences either by draping of sediments over earlier structures, or by differential compaction; and the absence of thinning argues against exposure and local erosion. Rather, they suggest a continuous differential subsidence of the structure, maintaining shallower waters on the crest which accumulated coarser and better sorted sediments than the surrounding deeper waters. This may be punctuated by upward pulsations on structure, or by intervals of stability, resulting on the one hand in thinning on structure, through erosion or nondeposition; or, on the other, in the deposition of a blanket type of deposit over the structure and surrounding area. In specific instances the stratigraphic column must be examined for these and other conditions in any combinations.

The case for regional subsidence in broad basin areas is more readily demonstrated than for local structures. Contemporaneous subsidence in the principal geosynclinal areas has been accepted since the time of Hall and Dana; and its occurrence in intracratonic basins is cited by numerous writers for many areas. The application of appropriate tests for contemporaneous tectonism thus permits

answer to Kay's second point: that in some instances the bottom surface of the stratigraphic unit was warped down during deposition.

The third of Kay's points, which relates to the attitude of the depositional surface during deposition, is a question of water depth during sediment accumulation. This point may be examined in terms of several criteria. Fossil indicators of depth are important in establishing shallow- and deep-water conditions; and the lithology of the sediments sheds considerable light on this question by the presence or absence of ripplemark, mudcracks, and the like. Kay (1945) cites a hypothetical instance which well illustrates the manner in which thickness, lithology, and faunal content permit narrowing of the interpretation. Studies by many workers have shown that the great bulk of sediments now exposed on the continent were deposited in shallow water. Barrell (1917) demonstrated that in regional terms, the surface of deposition may be considered essentially horizontal in many of the ancient seas. Moore (1929) concluded that the widespread seas of the Mid-Continent Pennsylvanian probably did not exceed 200 feet in depth; and Elias (1937) cites evidence for a maximum depth of about 180 feet during Permian time in Kansas. Considering the great areal extent of these seas, it is not improper in most regional studies to use a horizontal datum at the top of a depositional sequence, to demonstrate the concurrent attitude of the base of the stratigraphic unit.

In local studies it is important to consider depth changes in more detail, and close studies of depth-indicators in lithologic composition or in faunal content are necessary, as in the parallel case for local contemporaneous tectonism.

CRITERIA OF SEDIMENTARY ENVIRONMENT

It is a paradox that although the presence of an environment is self-evident from the occurrence of a sediment, the reconstruction of that environment is much more difficult than the reconstruction of contemporaneous tectonism. It is possible from an examination of a stratigraphic section to group the sediments into units indicative of certain broad tectonic conditions, as shelf associations, basin associations, *et cetera*. A degree of tectonism ordinarily occurs for a long enough time in any area to impress its characteristics on the stratigraphic column; but during this time the environment may pass through many phases.

Methods have been developed for expressing the lithologic, biologic, and tectonic aspects of a stratigraphic unit in terms of lithofacies, biofacies, and tectofacies (Sloss, Krumbein, and Dapples, 1949). Equally satisfactory methods for expressing sedimentary environment are not yet available, although some progress has been made. The difficulty in evaluating ancient environments stems from at least two causes. First, not enough is known about the details of modern environments to permit generalizations about the expected variations in ancient sedimentary patterns for alluvial plains, littoral zones, shallow neritic environments, and the like. Second, the geographic pattern of environments changes through time, so that a three-dimensional expression of environment involves

evaluation of the rapidity and direction of the change.

Inasmuch as finite thicknesses of rock must be used in regional or local studies, the problem of environmental reconstruction becomes one of expressing the section in terms of a specific environment, a dominant environment, a characteristic association of environments, or an "average" environment. In some instances this may be done with assurance. An evaporite basin with alternations of limestone, dolomite, and gypsum, and with characteristic assemblages of normal and aberrant faunas, permits fairly clear reconstruction of the flow of environments through the time represented by the stratigraphic column. A Pennsylvanian cyclothem, on the other hand, comprising marine and non-marine beds and including such divergent deposits as coal and fusulinid limestone, presents a much more difficult problem of expressing any dominant or average environmental condition.

Additional complexity in evaluating environment lies in the different lengths of time during which environmental agents may operate on the sediments before final burial. Barrell (1917) has shown that deposition occurs only when base level rises to permit accumulation of sediments to its surface. Baselevel may be determined by the effective depth of wave or current action; and when it remains stationary, the detritus on the surface is shifted here and there until it reaches some area below the depositional baselevel. Under stable shelf conditions the slow rate of subsidence means that the environmental agents may operate on the material long enough to impress their characteristics fully on the sediment in terms of textural and other features. On the other hand, in a rapidly subsiding basin or geosyncline the time available for sorting action is limited by the rapidity of burial, so that the environmental impress is much lighter.

As a consequence, beach sands formed on a stable shelf show all the attributes of typical quartzose sands, such as good sorting, good rounding, cross-bedding, and the like. Beach sands formed along the strand line of a more rapidly subsiding area may be poorly sorted subgraywacke sands, difficult to recognize as typical beach deposits. In the first instance the reconstruction of the environment generally narrows itself to a choice between beach and dune deposits (as in the St. Peter sandstone of the upper Mississippi Valley); whereas in the second instance it may not be possible to choose between alluvial and beach environments in the absence of contributory faunal evidence. An example of the latter may be seen in the Bartlesville shoestring sands, which have been interpreted both as stream-channel deposits and beach deposits. The linear form apparently fits either case. The Bartlesville sand occurs in a cyclical sequence which suggests either unstable shelf or basin margin conditions.

It is evident that criteria for distinguishing environmental groups must be threaded through the lithologic associations controlled by contemporary tectonism. Some environments may occur anywhere with respect to the tectonic framework, whereas others may be confined to certain elements of the framework. The strand line, in general, may occupy any position over a shelf area or even within a geosyncline; whereas a restricted environment of persistent evaporite deposition

is probably always associated with tectonically or biohermally controlled basin environment. If the strand line lies on a stable shelf area, it may occupy a narrow geographic zone for considerable intervals of time. If it lies on an unstable shelf, it may fluctuate widely to and fro. In a geosyncline the strand may either fluctuate, or it may show a systematic retreat as the geosynclinical deposits displace the strand toward the craton.

In contrast to the environmental shift from marine to continental phases which occurs when the strand line fluctuates across an unstable area, one may consider the neritic environment on an unstable shelf. If the oscillations are not great enough to displace the sea, the environment may remain neritic throughout, with simply a change in water depth as the oscillations occur. Such changes may bring with them changes in the depth-sensitive faunal elements; or they may be evidenced by alternations of shale and limestone. In short, when the factor of contemporaneous tectonism is combined with the environmental influence, it becomes possible to discern systematic environmental changes associated with certain tectonic influences.

These intimate relations between tectonism and environment suggest combined tectono-environmental classifications of sediments. Such classifications attempt to associate typical environments with certain broad tectonic areas, to indicate the dominant type of sediments which may occur within the tectonic framework.

TECTONO-ENVIRONMENTAL CLASSIFICATIONS

Tercier (1940) was among the first to set up a classification of tectonically controlled environments. He recognized five classes, as follows.

1. Areas of continental sedimentation on the continental platform. These include alluvial, lacustrine, glacial, etc.
2. Areas of the continental platform with paralic sedimentation, i.e., interfingered marine and continental sediments. Here are included alluvial, lagoonal, littoral, and shallow neritic environments. Coal cyclothems are typical of this group.
3. Areas of epicontinental marine sedimentation on the continental platform. Non-clastics dominate, as in the early Paleozoic of the Mississippi Valley.
4. Areas of geosynclinal sedimentation, with typically thick and heterogeneous accumulations.
5. Areas of deep-sea oceanic sedimentation. Here are included exclusively marine siliceous and organic chemical sediments in abyssal depths remote from land.

More recently, Pettijohn (1949) developed a classification of environments, with the following groups.

1. Basins of tectonic origin.
   A. Geosynclinal downwarps, with orogenic sedimentation, including marginal and axial facies.
   B. Epeirogenic downwarps, which include shelf seas and basins freely connected with the oceans; basins restricted and connected with the oceans by narrow inlets or shallow thresholds; and isolated basins, with no connection with the sea. The restricted basins yield black shale facies in humid areas, evaporites in arid conditions.
   C. Post-geosynclinal fault troughs with terrestrial sediments.
2. Non-tectonic basins, which include gradational and volcanic deposits.
3. Permanent deep-sea basins, with bathyal and abyssal deposits.

Both Tercier's and Pettijohn's classifications set the environments within their fundamental tectonic framework, and hence include the effects both of the sedimentary environment itself and the contemporaneous tectonism which sets

the stage for the depositional cycle. The writers have proposed a tectonic classification (Dapples, Krumbein, Sloss, 1948) which recognizes several typical associations of sediments developed under a range of tectonic conditions from essential stability (slow and relatively slight subsidence), to the more orogenic movements of geosynclinal and arkose basin sedimentation. It was pointed out that practically any kind of environment can occur under any of the tectonic conditions, and that its effectiveness in controlling sedimentary properties was a function in part of rate of burial.

In order to weave the environmental aspects more closely into the tectonic classification, a tectono-environmental classification is designed for sedimentary-stratigraphic work involving finite thicknesses of rocks. The common occurrence of sediments which show evidences of interbedded, intertongued, and intergradational deposits of more than one environment, suggests the grouping of associated environments for stratigraphic analysis, rather than specific environments, which usually can not be identified except under optimum conditions. The typical association of fluvial, lacustrine, and eolian sands and shales in continental sections, with sporadic thin-bedded or nodular fresh-water limestones suggests a grouping of these three environments under differing conditions of contemporaneous tectonism, such as their occurrence on shelves, in intracratonic basins, and in geosynclines. Similarly, the common association of fluvial, lagoonal, littoral, and shallow neritic sediments in the transition zone between dominant continental and marine beds suggests such a group as an intermediary, also considered in terms of contemporaneous tectonism. Finally, several subdivisions of the neritic environment are possible, to afford a spread of environmental associations from one extreme of depths to another. Where the data support specific environmental interpretation, or as knowledge increases, more refined subdivisions are possible.

PROPOSED TECTONO-ENVIRONMENTAL CLASSIFICATION

CONTINENTAL (FLUVIAL-LACUSTRINE-EOLIAN) ENVIRONMENT

The general characteristics of this group of environments includes the mutual operation of streams and wind on alluvial plains (piedmonts, broad deltaic plains, wide stream valleys, *et cetera*), combined with the occurrence of lakes and ponds, some with restricted circulation, others along the main channels. In such a combination environment the variety of sedimentary deposits may be large, but in general they are characterized by gray, brown, yellow, red, maroon, or white color, partly as a function of the oxidizing conditions and climatic features of the depositional area. The sandstones are commonly lenticular, with local conglomeratic zones, although sheet sands also occur. The shales are commonly massive or poorly bedded, with clay shales typical; they may be micaceous or carbonaceous, but few are calcareous. The limestones are subordinate, nodular or concretionary, here and there irregularly thin-bedded, with dense or uneven sugary texture, and are of the "fresh-water" type. Fossils may be locally abundant but are probably poor in the number of species represented. Plant impressions

may be common in the sandstones, and coaly or lignitic beds may be present.

The characteristics of the specific sediments which occur in this combination environment depend in part on the tectonic intensity in the depositional site. On stable shelves the sandstones are most commonly quartzose, and may include quartz-iron oxide, quartz-muscovite, or feldspathic quartzose varieties. The Entrada sandstone of the Colorado Plateau area is an example. Shales are commonly massive to poorly bedded claystones, commonly mottled. Limestones may be present as thin lenticular light-colored beds. Toward the source area the sands may dominate; over large areas the clay shales are dominant; and limestones are everywhere subordinate as far as known.

In less stable depositional environments, as on the unstable shelf, the sandstones tend to be poorly sorted, and are subgraywackes, with mica, and carbonaceous flakes; vertebrate bones and plant impressions are more common. The basal sandstones of Carbondale and McLeansboro cyclothems in Illinois are examples. Local occurrences of "channel sands" are thicker and cleaner than more widespread varieties. The shales change to siltstones, commonly micaceous and carbonaceous, although claystones are also present. Limestones are mainly dense nodular, with some localized thin-bedded lenses. Such limestones also occur in the lower parts of Illinois cyclothems. Lignitic or coaly zones are more prominent than in the stable shelf occurrence.

In intracratonic basins, with more marked subsidence than on shelf areas, the rate of burial is more rapid, the sediments are increasingly poorly sorted, and the sequence is thicker than on the shelf. Alternations of subgraywacke sandstone and silty shale in monotonous sequence, interrupted by lignitic beds and a few prominent nodular algal and massive limestones, are typical. The Bridger and Green River of Wyoming furnish examples. Some arkose wedges may occur in basin associations, giving rise in this environmental complex to typical associations of reddish arkosic sandstone and conglomerate, kaolinitic shales and very subordinate dove-colored types of non-marine limestone.

In the geosyncline this combination of environments occurs when deposition is more rapid than subsidence, so that the strand-line retreats and broad alluvial plains or deltaic tongues are formed, as in late Ordovician and late Devonian of the Appalachian area. The over-all aspect of the sediments is similar to the less intense tectonic stages, but the sands are true graywackes with subordinate subgraywacke. Conglomerates may be common and locally form linear bodies of considerable thickness, as in the Frontier of westernmost Wyoming. The shales are commonly chloritic or feldspathic, and may range from massive clay shales to coarse sandy siltstones. Fresh-water limestones may locally form rather thick lenticular bodies, commonly thin-bedded and irregular.

TRANSITIONAL (FLUVIAL-LAGOONAL-LITTORAL) ENVIRONMENT

This group of environments includes the transition from continental to marine deposition, ranging from alluvial plains and stream channels through lagoon-fringed shores to barrier beaches and shallow nearshore waters; or portions of del-

taic complexes; or the transition directly from fluvial to beach conditions without extensive lagoon development. This environmental zone is difficult to recognize in many geologic sections, because of the occurrence of broad transition zones in areas where the strand line shifts to and fro during the depositional cycle. The deposits tend to show much interfingering and gradation, with numerous lenticular bodies and tongues. In optimum conditions there is intercalation of dominantly brown or reddish shales and sands with dominantly bluish gray, greenish gray and black; but commonly the distinctions are not so clear.

In general characteristics the sediments display gray, brown, red, green, blue, dark gray, and black colors, as well as mottlings of reddish, purplish, and greenish varieties. The sandstones vary from quartzose to subgraywacke, depending on the tectonic setting of the environment. Shales may be claystones or siltstones, micaceous, carbonaceous, or calcareous; they may range in texture from massive to relatively uniformbedded. Limestones are ordinarily subordinate, but may include lenticular fresh-water types, marly varieties, or thin marine tongues. Fossils include alternations of terrestrial, brackish, and shallow marine types. Lignitic or coaly beds may be common.

On stable shelf areas this environmental zone may be identified as a belt with linear quartzose sand bodies, commonly with brackish- to fresh-water shales along one edge, and more typical marine shales or siltstones on the other. In some instances of dominant sand deposition, the transition may be from fluvial and eolian (dune) sands to beach or shallow marine types, with no intervening zone of shale.

On unstable shelves, where the strand-line shift may be more marked than on stable shelves, the associated deposits form cyclical successions, with beds ranging from purely continental types to marine neritic. The intertonguing Mesa Verde of eastern Utah is an example. Where the strand-line shift is not so extensive, the cyclical repetition of beds may lack typical marine shales or limestones, and consist mainly of basal subgraywacke sands, fresh-water clay shales, and coaly or lignitic beds, as in the Tongue River formation of Montana. "Channel sands" or other linear sand bodies of a cleaner subgraywacke or quartzose type may be common in the sequence.

In intracratonic basins thickening of the shale sequences is prominent, and there appears to be a general increase in the lenticularity of the units. Rapid sand and shale pinch-outs may occur, and a single sequence of shale may show progressive change from marine through brackish to continental characteristics. In general the shales are more silty than the shelf equivalents, and the clean sand lenses are more sporadic and commonly thicker. Cyclical units are also thicker, and some coals are better developed, though more widely spaced, than in shelf cyclothems. In general, progression from marginal to axial parts of the basin is accompanied by increase in the proportion of marine beds, as in the Tertiary of the Gulf Coast.

In the geosyncline it may be difficult to identify this environmental group as

a unit, because of rapid burial and rapid lateral shifts in environment. The intensity of tectonism, in its control of the rapid rate of burial, may be great enough to obscure environmental patterns.

The wide range of conditions commonly extant in the transitional environmental group suggests that where possible the transitional environments be expressed within narrower limits. Fluvial-lagoonal transitions may be recognized, or lagoonal-littoral, or littoral-neritic. Where control is closely spaced and the stratigraphic thickness is limited, it may be possible to differentiate each environmental band, as Bass (1936) did in his study of the Cherokee of southeastern Kansas.

EPINERITIC ENVIRONMENT

The neritic environment is defined as the zone between low tide and a depth of 100 fathoms. Scott (1940) subdivided this range into two classes, which he defined as epineritic (0 to 20 fathoms), and infraneritic (20 to 100 fathoms). This usage is followed here, because of the importance of distinguishing the more shallow parts of the environment from the deeper. In the epineritic zone current action may be prominent, and the greater nearness to land may result in more sand and shale in the section than in infraneritic zones. The epineritic zone also has areas of clear water, which may develop biostromal conditions, giving rise to dominant carbonate deposits.

Although the limits of bathymetric zones may be defined in terms of depths in recent seas, it must be recognized that the use of these bathymetric terms in discussing ancient environments carries an implication of similar conditions in each zone, but without restriction to the same specific depth limits. Thus, discussion of the neritic zone in the Paleozoic does not imply that the zone extended to precisely 100 fathoms, but that the deposits show the characteristics of relatively shallow water rather than of bathyal or abyssal depths.

The deposits of the epineritic environment are wholly marine, commonly with light gray, brown, greenish, or bluish colors in the shale, although local or widespread red or black shales may be present. Sandstones tend to be relatively well bedded and fine-textured, with cross-bedding and ripplemark common. Limestones show a wide range from dense argillaceous to fossiliferous-fragmental varieties.

The epineritic zone is characterized by an enormous profusion of organisms, dominated by benthonic types, and many susceptible to preservation as fossils. Most wave lengths of light can penetrate to all parts of the epineritic bottom, promoting the growth of a rich flora which in turn supports, directly or indirectly, a varied fauna. It is difficult to generalize about the forms to be expected, since a succession of dominant or prevalent types with advancing geologic time is evidenced by the fossil record. In near-shore areas where wave action is an important influence thick-shelled pelecypods and gastropods are characteristic. In the offshore areas a great range of invertebrate phyla are represented, and, in the ab-

sence of abundant land-derived detritus, fossil materials, commonly dislocated or fragmented, compose the bulk of accumulated sediment. Locally, reefs may be formed by associations of lime-secreting animals and algae of many types.

The epineritic environment on the stable shelf is a site of maximum environmental control of sedimentary properties. The gentle rate of subsidence, combined commonly with a slow rate of detrital supply, affords the environmental agents an opportunity of exerting maximum transporting and sorting effects before sediment burial. Widespread sheets of quartzose sandstone, thin clay shales, and limestones with clastic textures may be common. Oölitic limestone may be associated with the more agitated zones of carbonate deposition. In many places the sandstones grade through calcareous varieties to limestone, without the intervention of argillaceous rocks.

With increasing instability of the depositional site the sediments are less uniformly well sorted. The sandstones contain more interstitial material; and the shales are silty and micaceous. Limestones commonly show less evidence of clastic texture, and more argillaceous or nodular types may appear. This tendency toward less environmental control of textural, and other characteristics under conditions of more rapid burial, become prominent in intracratonic basins, and reach a climax of heterogeneity in the geosynclines.

The epineritic environment was one of the most common and widespread environments in the geological past. Evidence increasingly supports the inference that the prevailing water depths in epicontinental seas were 200 feet or less in depth, with a substantial area under 120 feet, which is the assumed deeper limit of the epineritic environment. The widespread limestones of the early and middle Paleozoic were apparently laid in epineritic waters on stable or mildly unstable shelves; the Pennsylvanian cyclothems represent a range from continental to epineritic conditions, with only the fusulinid limestones requiring waters as deep as 180–200 feet.

The epineritic environment relatively remote from land, and free of significant amounts of land-derived detritus, may develop strong biostromal tendencies, in which a rich benthonic fauna occupies the bottom. Slight shifts in temperature, salinity, oxygen content, water depth, or other factors, may develop conditions locally suitable for the development of bioherms, which rise above the bottom as compact colonies of organisms. On stable shelves such biohermal growths appear to be randomly distributed, but the bioherms tend to develop linear reef belts along tectonic hinge lines at the margins of more rapidly subsiding areas.

Because of the importance of such biostromal conditions in the development of limestone reservoirs, it is probably desirable where possible to differentiate the biostromal epineritic environment from the epineritic environment dominated by land-derived detritus, which gives rise to shale and sand sections with subordinate limestones.

INFRANERITIC ENVIRONMENT

The infraneritic environment includes water depths ranging from 120 to 600 feet. In general the water is quieter than in the epineritic environment, so that

less evidence of cross-bedding and ripplemark occurs in infraneritic deposits. Relatively quiet waters also provide conditions for well developed bedding in sands and shales, in the absence of mud-burrowing organisms, which may destroy bedding. The clastic sediments in the infraneritic environment are commonly finer than in the epineritic, and chemical or biologic sediments commonly dominate. Conditions of water temperature, clarity, salinity, dissolved-gas content, and other physico-chemical factors are more important than those dependent on the mechanical energy of the environment.

The colors of sediments deposited in the infraneritic environment show a wide range, with gray, greenish gray, bluish gray, and brownish gray common; dark gray and black types may occur, and reds and dark browns are subordinate. The sandstones are mainly thin-bedded sheet sands or broad lenses. The shales are commonly well bedded clay shales. The limestones may occur in wide variety ranging from some fossiliferous-fragmental types, swept in from shallower water, to denser partly siliceous varieties. Benthonic fusulinid types of limestone are very common in the deposits of late Paleozoic seas of water depth of 200 feet. The dense organically rich black limestones found in some basin deposits, as the Bone Spring of Texas, are believed to have formed in the deeper parts of the infraneritic environment, or possibly in bathyal depths.

Biologically, the infraneritic environment is gradational between the wave-agitated epineritic zone and the depth limit of photosynthesis. The shallower parts are populated by a fauna fully as rich and varied as that of the epineritic, but differentiated by the presence of more delicate and thin-shelled forms. In deeper waters the flora is progressively reduced (except for phytoplankton), fewer benthonic animals are found, and planktonic contributions to the fossil record rise in relative importance as the edge of the bathyal zone is approached.

On the stable shelf the infraneritic deposits represent a deeper-water phase of the epineritic deposits, with the main distinction one of faunal elements in the rocks. It is believed that many fossiliferous limestones composed of benthonic forms are developed in water depths ranging from 100 to 200 feet, a zone straddling the bathymetric zonal boundaries. Elias has shown (1936) that fusulinid limestones are associated with water depths of the order of 180 feet; and Moore (1929) suggests that most Mid-Continent Pennsylvanian deposits were formed in water depths of less than 200 feet. Scott (1940) analyzed the depth implications of Cretaceous ammonites, and based his original subdivision of epineritic and infraneritic depths on his findings.

Normal marine limestones, composed of fine- to medium-textured carbonate particles, and without conspicuous fossil content, appear to have resulted from inorganic precipitation of carbonate, or from the contributions of algae. It is believed that such limestones find their optimum conditions for formation in relatively shallow water, but it is probable that they are more common in infraneritic than epineritic depths. The widespread occurrence of normal marine limestones in the early Paleozoic of the central states suggests their formation in the central parts of the very extensive epicontinental seas of that time, under

conditions of mild subsidence on stable or unstable shelves.

The effect of minor oscillations in the tectonic intensity is felt less and less as deeper environments are attained. Whereas a decrease of 50 feet in sea-level has a profound effect on the conditions adjoining a low strand, the same change in water depths of several hundred feet is relatively minor. In the first instance the environment changes from marine to continental in a wide band; and even the epineritic conditions may be strongly affected by the shallowing. In the infraneritic environment, the change in water depth in no way changes the essential marine nature of the deposits. The lag in faunal response to slight depth changes may therefore blur the effect of relatively short oscillations.

As tectonic intensity increases, even the deeper infraneritic environment may show its effects in alternations of clastics and carbonate rocks, or in the specific types of limestones formed.

In the deeper parts of the infraneritic environment it is thought that the sediments develop more siliceous qualities and darker colors. Typical splinter shales and pencil shales, such as are seen in the Smithwick of central Texas, may represent deposits laid in depths of several hundred feet, under conditions of moderate tectonic intensity. At somewhat lesser depths, yet within the infraneritic range, the shales become dark. In intracratonic basins, where subsidence may draw the central part of the depositional area below depths of 120 feet, typical sequences of dark basin shales, thin dark limestones, and very minor sandstones, are developed. This is illustrated by some of the Pennsylvanian deposits in the Anadarko basin.

As with the epineritic environment, the infraneritic environment may be dominantly biostromal, with its attendant maximum importance of organically derived non-clastic sediments.

BATHYAL AND ABYSSAL ENVIRONMENTS

It is doubtful whether sediments formed in bathyal or abyssal depths occur in the stratigraphic column of the continents except locally within geosynclinal sequences, and perhaps rarely in intracratonic basins. In the orogenic eugeosynclinal belt the occurrence of such deep environments must represent times of marked regional subsidence sufficient to submerge the positive elements which normally feed detritus into the troughs. Under such conditions the sediments from the lands are fine-grained and of relatively minor amount; and emphas is is on chemical sediments formed below the depth limit for abundant benthonic life. The resulting sediments are highly siliceous, and may represent chert beds as in the Franciscan of California; or an intimate mixture of silica and carbonate to produce a dense siliceous limestone. Associated fossils include such siliceous types as sponge spicules and radiolaria. Some of the limestone may be the black, organically rich sediments mentioned in the infraneritic environment. Very siliceous splintery dark shales may also be represented in this association.

If the inferences developed in connection with bathyal and abyssal deposits

are approximately correct, there would be no occurrences of these deposits in shelf associations; they would be very rare in intracratonic basin associations; and only local and sporadic in the more eugeosynclinal parts of linear geosynclinal belts.

RESTRICTED LAGOONAL ENVIRONMENT (HUMID)

There are many evidences in the geological column of sediments deposited under restricted environmental conditions. These evidences include the occurrence of special lithologic conditions or aberrant faunas. Two general conditions may be recognized, in the first of which there is evidence of restriction within tectonic basins, commonly aided by biohermal control; and in the second the restriction occurs in broad or local shelf areas due to the presence of barrier beaches, submerged sills, and the like. The climate in which the restriction occurs is of basic importance, inasmuch as it largely controls the relation among inflow, precipitation, and evaporation. The resulting deposits differ markedly under humid and arid conditions, and these two conditions require separate treatment.

In humid climates the restricted area does not suffer marked reductions in volume due to evaporation and may become brackish from rainfall or run-off. The most important environmental features are associated with stagnation of the waters. Under these circumstances there is a high incidence of hydrogen sulphide in the restricted waters, and a general lack of oxygen. Fleming and Revelle (1939) discuss the general conditions in stagnant fjords, which may be taken as typical. Organisms are confined to the upper waters, and benthonic forms are rare or absent. The bottom muds may contain a high percentage of organic matter derived from dead plankton which settles to the bottom. Anaerobic bacteria only partly decompose the organic matter, and attack the sulphates, to produce hydrogen sulphide. This in turn reacts with iron salts and produces black iron sulphide.

As a consequence of the environmental conditions, the sediments are dark gray to black, and consist dominantly of black bituminous and pyritic shales, ordinarily fine-textured, well bedded, or fissile. Limestones, where present, are dark, bituminous, and thin-bedded. The faunas may be dominated by a few planktonic or nektonic types capable of withstanding brackish conditions, occasional high temperatures, low oxygen content, and the noxious effects of displaced sulphate equilibria. Bottom-dwelling forms are few in number and species. Phosphatic brachiopods, certain mud-dwelling clams, and such poorly understood types as conodonts are probably the only forms represented in the fossil record.

In shelf occurrences, restricted conditions may occur behind barrier beaches or fringing coral reefs in lagoons sealed from access to the open sea by tectonic movement, by eustatic changes of sea-level, by biologic control, and by other causes. In some instances, as in the black paper shales of the Pennsylvanian cyclothems, it has been suggested that abundant growth of sea weeds in shallow marine waters may so inhibit circulation as to develop restricted conditions. The common associ-

ation of dwarfed and aberrant faunas in such shales supports the idea.

Dark clay shales and fine siltstones, in general relatively thin, and interbedded with sediments deposited under open conditions, appear to be the rule in shelf occurrences of this environment, and they may be widespread. The sediments grade laterally into continental sediments; and may grade into or intertongue with normal neritic sediments along one margin. Sandstones and limestones are relatively rare in restricted shelf sequences.

In intracratonic basins dark shales are common, but it is not certain to what extent restrictions may have occurred in typical basin shale accumulations. It is probably preferable to infer open circulation conditions for most dark basin shales (such as the Pennsylvanian sequences in the Anadarko basin) in the absence of criteria such as pyrite, aberrant faunas, and associated restricted limestones. Sandstones are minor in occurrence, and include subgraywackes with relatively high organic content in the form of carbonaceous or bituminous material. Under conditions of greater tectonic subsidence, as in geosynclines, the black shales of the humid restricted environment are more silty and less even-textured; and the associated sandstones are graywackes or fine-grained salt-and-pepper sands. Limestones are rare or absent.

The very extensive black shales of the Chattanooga type contain some evidences of formation under restricted conditions. Their wide extent and relative thickness, however, argue against complete stagnation of an entire epicontinental sea. Some controversy remains on the depth of water under which such shales form. It is the writers' opinion that these shales are mainly shelf varieties, deposited in the epineritic zone, under restricted conditions promoted by widespread shallow depths with circulation impeded by algal growths. If these seas were very shallow, and circulation impeded as assumed, it would appear that rainfall must have been in excess of evaporation, or evaporites would be associated with these black shales.

RESTRICTED LAGOONAL ENVIRONMENT (ARID)

The same conditions which may restrict circulation in humid climates may operate in arid climates, but as soon as restriction is accomplished, the aridity results in reduction of the volume of restricted waters. Under these conditions the normal sea water becomes hypersaline; and if evaporation proceeds far enough, evaporites may be deposited in the restricted area.

The change in salinity is accompanied by a marked change in the fauna which can inhabit the area. The great majority of marine pelagic and benthonic types are excluded and replaced by a small number of species of specialized plankton. These are typically without calcareous shells or tests and contribute little recognizable material to the fossil record.

The sediments formed under restricted conditions in arid climates are dominantly light-colored, with white, cream, light brown, light green, pink, and red colors most common. The shales are gypsiferous, and the limestones are commonly dense, thin, and dolomitic. Sandstones are relatively rare.

On stable or unstable shelves the evaporitic associations may be relatively widespread. They grade laterally into and are commonly interbedded with red-bed sequences on the landward side, and they may show relations similar to normal marine or biohermal sediments along the opposite margin. King (1942) shows on Permian lithofacies maps several excellent examples of such relations. The associated sandstones are quartzose or clean subgraywackes, with iron-oxide staining a common attribute. Thin gypsum or anhydrite beds, commonly lenticular, are a feature of the association.

The most typical occurrence of thick deposits of evaporites is in intracratonic basins, where the restriction of the basin is accomplished by the growth of bioherms in rings along the tectonic hinge at the basin edge. If restriction is complete, a dominantly evaporite sequence may develop in the basin; more typically the deposits show a cyclical alternation of limestone, dolomite, thin clay shales, and evaporites. These alternations may be attributed to combinations of tectonic intensity, rise or fall of the outer sea, or to withdrawal of the outer sea, leaving behind a relict sea which evaporates to dryness.

It is doubtful whether thick or extensive evaporite associations occur in geosynclinal conditions, because of the high degree of instability, which prevents any set of conditions from existing long enough to produce evaporite sections such as are common in intracratonic basins. When the geosyncline is filled, and broad deltas occupy the shore zone, local areas of gypsiferous sandstones or shales may be formed. The occurrence of typical graywacke sandstones and the general absence of limestones in the section aid in interpreting such occurrences.

Table I is included for ease of comparison of the environmental associations. The material is much condensed from the text, but it indicates that through all environments the sandstones are generally quartzose in stable shelf conditions, subgraywackes in unstable shelf and intracratonic conditions, and predominantly graywackes in geosynclinal conditions. These common denominators of all environments must be discounted, therefore, as having any particular bearing on environmental interpretation. Rather, it is the association of particular combinations and relative abundances of sandstones, shales, and limestones which serves as an environmental index, combined with a critical analysis of such faunal elements as are contained in the sediments. The application of this table to stratigraphic analysis is deferred to a later section.

SEQUENCE OF EVENTS IN DEPOSITIONAL CYCLES ON CRATON

It is apparent from the foregoing sections that fundamental to any discussion of environment and tectonism is the broad framework in which the depositional cycle occurs. The tectonic framework of sedimentation includes the number, kinds, and relative geographic positions of sedimentary basins, geosynclines, neutral areas, and positives. These comprise the complex of source area, paths of transportation, and sites of deposition of a stratigraphic unit. Over this framework spread the epicontinental sea whose strand line marks the division between

TABLE I

Tectono-Environmental Classification

(This table is generalized and simplified for ease of reference. Consult accompanying text for additional details)

	Fluvial-Lacustrine-Eolian Environment	*Transitional Environment (Fluvial-Lagoonal-Littoral)*	*Epineritic Environment*	*Infraneritic Environment*
General conditions; types of specific environments	Alluvial plains, stream channels, lakes, swamps, local or extensive wind action.	Alluvial plains, lagoons, marshes or swamps, barrier beaches, deltaic conditions.	Shallow wave and current-agitated marine waters, open circulation.	Water depths exceed 120 feet; relatively quiet offshore zones.
General colors and properties of sediments; main faunal elements	White, gray, yellow, red, brown, maroon, mottled. Lenticular or sheet sandstones. Blocky to poorly bedded shales. Limestones very subordinate; coal and lignite beds. Plant impressions and remains; land vertebrates; fresh-water gastropods and pelecypods.	Gray, brown, red, green, blue, dark gray, and black. Lenticular sandstones; some sheet sands. Shales blocky to well bedded; coal and lignite beds. Limestones subordinate; here and there a tongue of marine limestone. Plants; land vertebrates, gastropods, pelecypods, phosphatic brachiopods, and ostracodes common.	Gray, light brown, greenish gray, bluish gray, dark gray to black. Sheet sandstones; local linear bodies. Shales commonly bedded; limestones range from argillaceous to fossiliferous-fragmental types. Great variety of stout-shelled benthonic invertebrates (mollusks, brachiopods, echinoderms, corals, etc.)	Sediment colors gray, greenish gray, bluish gray, brownish gray, dark gray, black. Reds and browns subordinate. Sheet sands mainly fine-grained; shales well bedded. Limestones show wide variety, with normal marine types dominant. Great variety of benthonic and nektobenthonic types, including more delicate forms. Significant percentages of planktonic types.
Stable Shelf Occurrence	Quartzose sandstones, cross-bedded. Massive clay shales, commonly mottled. Carbonaceous; seldom calcareous. Fresh-water limestones, nodular, dense, local.	Quartzose sandstones, cross-bedded, commonly lenticular. Clay shales dominant, brackish varieties bedded; carbonaceous, locally calcareous, marly. Fresh-water limestone subordinate.	Quartzose sandstone cross-bedded. Siltstones ripple-marked. Shales commonly fine clayey, and greenish. Limestones with clastic textures, evenly bedded or locally cross-bedded. Sandstone may grade directly to limestone.	Fine-grained quartzose sandstones. Clay shales common, well bedded; calcareous, carbonaceous. Limestones normal marine, fusulinid, chalk; numerous planktonic components.
Unstable Shelf Occurrence	Subgraywacke sandstones, some linear quartzose channel sands. Shales mainly siltstones, massive to banded, micaceous, carbonaceous, seldom calcareous. Fresh-water limestones subordinate, nodular dense to uneven sugary texture.	Lenticular quartzose sandstones; sheet sands are subgraywacke. Shales mainly siltstone; claystones commonly bedded; micaceous, carbonaceous, calcareous. Fresh-water to marly limestones.	Quartzose to subgraywacke sandstones, cross-bedded, ripplemarked. Shales commonly siltstones, carbonaceous, calcareous, light colors. Limestones thicker stable neritic types, argillaceous, locally denser.	Fine-grained to subgraywacke sandstones, evenly bedded. Silty claystones, carbonaceous, calcareous. Limestones as above, locally denser, less widespread.
Intracratonic Basin Occurrence	Subgraywacke sandstones, local arkose associations. Shales mainly uneven-textured siltstones; micaceous, carbonaceous, semi-waxy, seldom calcareous. Limestones nodular to uneven thin-bedded.	Quartzose, subgraywacke, arkosic sandstones; thick shales commonly change characteristics from top to bottom. Micaceous, carbonaceous, calcareous. Fresh-water limestones may locally be thick.	Subgraywacke sandstones, arkosic sheets or wedges. Shales silty, carbonaceous, micaceous, calcareous. Limestones nodular, uneven, may be argillaceous or dense.	Subgraywacke sandstones, thin-bedded. Shales fine siltstones to clay shales; dark colors common. Limestones thin, commonly dark; may be nodular.
Geosynclinal Occurrence	Graywacke sandstones with subordinate subgraywacke channels. Shales massive to banded, chloritic or feldspathic. Fresh-water limestone may form thick lenticular bodies.	Graywacke sandstones with subordinate subgraywackes. Massive to banded shales, mainly silty to sandy. Local thick fresh-water limestones.	Graywacke sandstones with thinner subgraywackes. Shales commonly uneven-bedded; may show dark colors. Limestones subordinate, nodular.	Graywacke sandstones subordinate. Shales mainly siltstones with uneven texture. Limestones rare; siliceous, dark.

<table>
<tr><th></th><th>Epineritic Biostromal Environment</th><th>Bathyal-Abyssal Environment</th><th>Restricted Lagoonal Humid</th><th>Restricted Lagoonal Arid</th></tr>
<tr><td>General conditions; types of specific environments</td><td>Shallow clear waters, open circulation, little or no land-derived sediment. Temperature, salinity, oxygen content, and depth are controlling factors.</td><td>Water depths exceed 600 feet; these conditions may locally be fulfilled in rapidly subsiding geosynclines. Rare or absent in craton.</td><td>Mainly neritic depths; volume may be constant, but circulation restricted by barriers, sills, or biohermal control.</td><td>Mainly epineritic depths; evaporation exceeds inflow. Circulation restricted by barriers, sills, or biohermal control.</td></tr>
<tr><td>General colors and properties of sediments; main faunal elements</td><td>Light colors, with tan, bluish, cream dominant. Sandstones and shales subordinate; main bulk of sediments are carbonates, with abundant evidence of life forms and associated debris. Corals, bryozoans, algae, oysters, specialized brachiopods and larger foraminifera, crinoids, etc.</td><td>Sediment colors commonly dark; blue, green, red, dark gray to black. Land-derived sediments relatively rare; shales siliceous, diatomaceous. Limestones dark siliceous. Chiefly planktonic types, smaller foraminifera, diatoms, pteropods, etc.</td><td>Sediment colors commonly dark gray to black. Sandstones rare; shales dominate; bituminous, pyritic; calcareous, mainly claystones. Limestones dark, bituminous, thin-bedded. Phosphatic brachiopods, conodonts, certain mollusks, spores, algae.</td><td>Sediment colors commonly light; white, cream, brownish, greenish, bluish, pink, red. Sandstones rare. Clay shales dominate, gypsiferous, calcareous. Limestones dense; primary dolomites, nodular to thin-bedded. Evaporites may range from subordinate to dominant. Fauna aberrant, depauperate or lacking.</td></tr>
<tr><td>Stable Shelf Occurrence</td><td rowspan="2">This is a typical environment of stable to mildly unstable shelves, in widespread shallow seas. The biostromal areas may occur locally or over large areas. Sporadic bioherms common. Limestones include fossiliferous-fragmental, reefoid, oölitic, and chalks. Subordinate clay shales, marls, and thin quartzose sands in the association.</td><td rowspan="4">These environmental conditions doubtfully present on shelf areas; may occur locally in intracratonic basins. Typical but rare occurrence in eugeosynclinal association at times of rapid subsidence and slow deposition. No sandstones known; shales very siliceous, splintery; primary chert beds or nodules; limestone dark, dense, very siliceous.</td><td rowspan="2">In shelf occurrences, this environment may form widespread black shales behind barrier beaches or fringing reefs. The sequence may grade into continental sands and shales on one or more sides. Within the environment sandstones and limestones are rare.</td><td rowspan="2">In shelf occurrences this environment may form widespread evaporitic sequences dominated by gypsiferous shales and thin evaporite beds, grading landward to typical redbed continental and transitional sequences. Limestones thin and subordinate within sequence.</td></tr>
<tr><td>Unstable Shelf Occurrence</td></tr>
<tr><td>Intracratonic Basin Occurrence</td><td rowspan="2">Under basin or geosynclinal conditions, biostromes may rarely occur in local optimum areas. Significant is the growth of biohermal zones along tectonic hinge lines at edges of intracratonic basins. Here reefoid, fragmental, oölitic limestones are the rule, with other types subordinate.</td><td>Thick sequences of dark shales, bituminous, waxy, mainly clay types. Sandstones rare, fine-grained. Limestones subordinate, dark, bituminous varieties.</td><td>Thick sequences of typical evaporite associations; gypsum, anhydrite, salt, thin limestones, and dolomites; bright-colored shales, commonly clayey and gypsiferous. Cyclical evaporites common.</td></tr>
<tr><td>Geosynclinal Occurrence</td><td>Dark gray, brown, greenish silty shales, uneven textures. Some fine graywackes or subgraywacke sandstones. Limestones rare or absent.</td><td>It is doubtful whether true evaporite basins occur in geosynclinal conditions, although local sheets of evaporitic beds and gypsiferous shales may be associated with deltaic parts of geosynclinal sedimentation.</td></tr>
</table>

continental and marine environments. The more positive areas and exposed neutral areas become the sites of subaerial erosion and fluvial and eolian transportation, as well as temporary sites of continental sedimentation along stream courses, in lakes and swamps, and on alluvial plains. Most of the detritus carried from the source area finds its way ultimately into the sea, where it is distributed through the littoral, neritic, and other bathymetric zones.

Studies of several years at Northwestern University have resulted in the collection of typical examples of regional sedimentary facies patterns. These examples display a variety of sedimentary and tectonic conditions. In order to integrate several conditions into a single example, some of the studies have been combined in a hypothetical case, to illustrate the sequence of events during a dep-

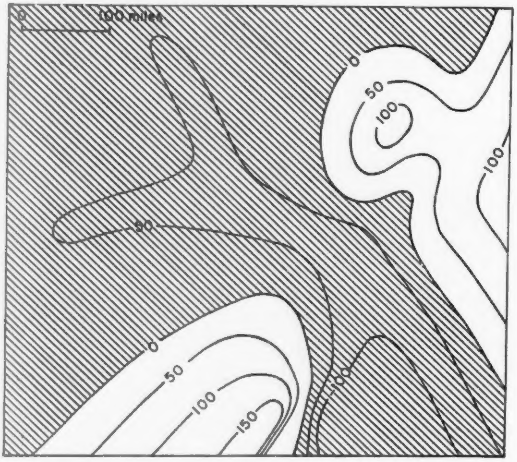

FIG. 1.—Hypothetical major cycle of late Paleozoic deposition, I. Initial stage.

ositional cycle in an idealized tectonic framework. The stratigraphic interval represents a stage in Pennsylvanian or Permian time, under conditions of semiaridity. Examples of the actual instances used are cited on a later page. It is assumed that previous to the idealized interval, the area (approximately 250,000 square miles) had been eroded essentially to a peneplain, so that the new major cycle represents deposition over a nearly level surface.

Figure 1 shows a generalized topographic map of the pre-depositional surface, at the inception of the new cycle. The land area has a relief of only a few hundred feet, with scattered erosional remnants. In the south-central area is an old granite terrane; in the east and northeast are scattered hills of basement rock, mainly metamorphosed sediments. The broad intervening area is underlain by deposits of the previous depositional cycle. The sea is assumed to invade this area from

the southeast, submerging the part indicated on the map. This invasion is initiated by a re-establishment of subsidence in the depositional area, and uplift in the source areas.

The tectonic framework of the new cycle of deposition is shown in Figure 2. The south-central granitic area develops a strong positive tendency, and is separated by a normal fault from a rapidly sinking block on the east. The higher areas along the east and northeast of the map area also developed positive tendencies, but epeirogenic rather than orogenic. The southeastern basin and the two positive areas act in a complementary manner, with the one sinking at nearly the same rate that the others rise. An additional area of subsidence occurs in the northwest,

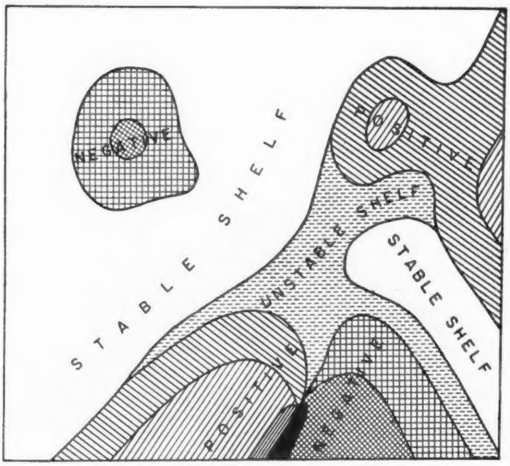

FIG. 2.—Cycle of deposition, II. Tectonic framework.

somewhat more remote from the complementary uplifts. The broad intervening area among the positive and negative elements is essentially neutral, that is gently subsiding, with some oscillations in the zone between the southern and northeastern positive areas. The tectonic activity is to be contemporaneous with deposition during the cycle.

Figure 3 shows the distribution of gross environments over this framework as a result of invasion by the sea under the operating tectonic influences. The higher parts of the positive areas now become sources, feeding detritus to the sea, where most rapid accumulation occurs in the subsiding basins. Part of the detritus temporarily accumulates as alluvial and lacustrine deposits on the lower land slopes, and passes through the transitional littoral zone into the epineritic environment. The transitional littoral zone is shown as approximately 100 miles wide, to represent fluctuations of the strand line during oscillations which occur at the borders of the more active tectonic areas.

It is apparent that the steeply faulted eastern side of the southern positive area will feed much clastic material into the eastern basin; whereas the more gentle northward slope will supply less abundant and probably more highly weathered débris toward its northern shore. The northeastern positive area spreads a sheet of mud and sand toward the sea and into the neritic environment. To illustrate the quartzose sand deposition, it is assumed that currents winnow out the fine materials, and move them southward along the eastern shore. The southern part of the eastern source area also supplies sand and mud to the neritic zone, and augments the mud supply from farther north. As a consequence of this

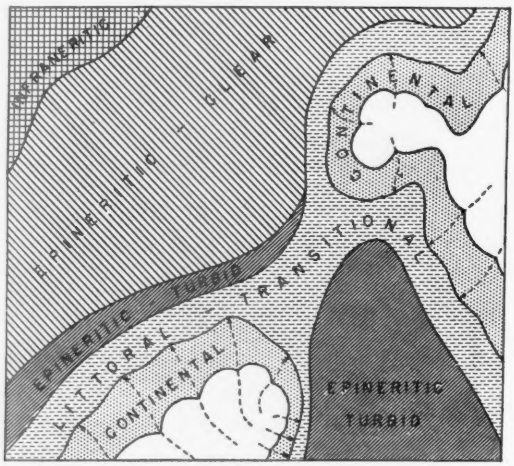

FIG. 3.—Cycle of deposition, III. Distribution of environments.

distribution of source areas, relative rates of erosion, and postulated currents, it may be expected that the general northwestern part of the neritic environment will have relatively clear waters, whereas the southeastern part of that environment will be more turbid.

An immediate response to the physico-chemical conditions of the environment is shown by the faunal assemblages which thrive in the map area, as indicated in Figure 4. Starting in the clear shallow seas of the northwest, benthonic fusulinids dominate in the farthest offshore areas, grading southeastward into a broad area dominated largely by a crinoidal fauna with scattered coral-algal bioherms. The tectonic hinge line along the edge of the northwestern subsiding area becomes the site of a ring of bioherms. This generally continuous reef trend will isolate the central part of the developing intracratonic basin from the free circulating waters on the outside of the reef belt. Such biohermal trends grow upward as the area subsides, maintaining the inner basin in a state of restricted circulation during the greater part of the depositional cycle.

Shoreward from the crinoidal area on the northeast the fauna grades into a typically molluscan type which is capable of thriving on the prevailing sandy bottoms. Elsewhere toward the shore, zones of productids and certain mollusks thrive in areas where the bottom is more muddy. In the southeastern part of the shallow sea, where partly restricted conditions may be prevalent, molluscan faunas and phosphatic brachiopods will be typical, grading westward to molluscan types in the more sandy areas near the fault source. Along the entire strand line, where the environments shift to and fro in response to sea-level changes, numerous faunal elements may be present. These include algae, pelecypods, *Lingula*,

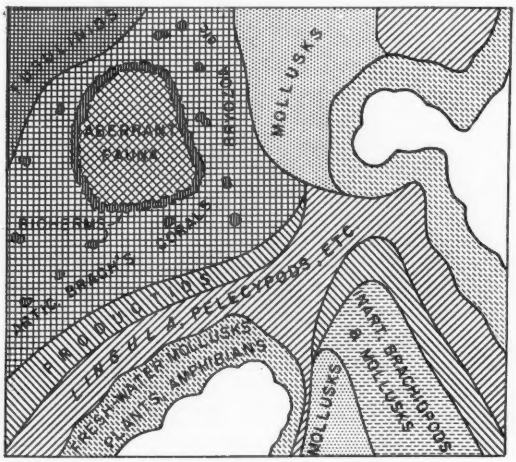

FIG. 4.—Cycle of deposition, IV. Biologic response to environmental distribution.

and some plant remains in the lagoonal environment. Landward from the zone of shifting strand lines, above sea-level, the continental deposits contain the remains of plants, fresh-water mollusks, and land vertebrates.

The biofacies response to the environmental and tectonic influence is very important in the development of sedimentary rocks in the clearer sea areas. Establishment of the biohermal ring at the edge of the northwestern intracratonic basin means that the environment within that ring is controlled primarily by restrictions due to biological agents; and the clearer sea areas dominated by crinoids or fusulinids accumulate typical shelf associations of fossiliferous fragmental limestones. Figure 5 shows the sedimentary response to the environmental conditions.

Within the zones in which clastic sedimentation dominates, a broad sheet of sand extends across the transitional and neritic environments in the northeast, as waves and currents winnow and distribute the material over the essentially

stable shelf area. Toward its western edge the sandstone grades into limestone through a transition zone of calcareous sandstone and sandy limestone, as Figure 5 indicates. Farther southeast, mixtures of sand and silt are deposited in the higher parts of the continental environment, becoming finer toward the sea, with increasing amounts of organic material added as lagoonal and other phases of the littoral-transitional environment are encountered. The northern part of the southwestern source area has a distribution of sediments much like the southern part of the eastern source area. In marked contrast to this are the deposits accumulating in the southeastern basin adjacent to the strong normal fault. The

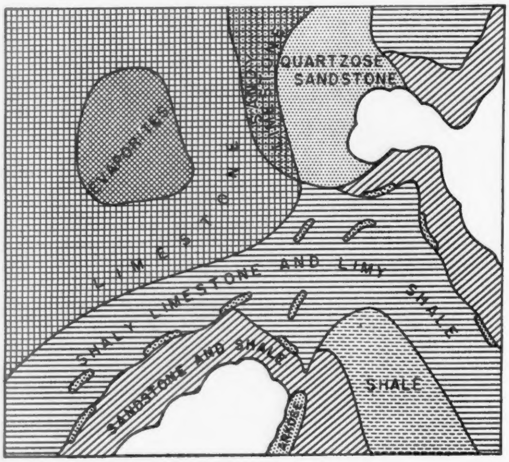

FIG. 5.—Cycle of deposition, V. Lithologic response to environmental and tectonic controls.

granitic terrain exposed to erosion feeds arkose into this basin, and the large rate of supply, combined with rapid burial, means that these arkoses are preserved in a poorly sorted state, and in the form of a very thick wedge. Farther east the material grades through an intervening zone of sandy shale to predominant shale deposition in the eastern part of the subsiding basin.

In the meantime, restricted circulation in the northwestern intracratonic basin, under conditions of semi-aridity, results in the development of an evaporite sequence in that basin. These evaporites consist mainly of alternations of limestone, dolomite, anhydrite, and possibly halite. Relatively few and thin clay shales may be interspersed with the dominantly chemical sediments, as a result of occasional tectonic pulsations which may feed mud into the lagoon through passes along the biohermal ring.

Several actual situations are illustrated in the hypothetical depositional cycle. For example, the widespread sheet of well sorted quartzose sand in the northeastern part of the map area, which grades from continental to shallow

marine types, is illustrated by the Tensleep sandstone of Montana and Wyoming. The Tensleep locally grades laterally into limestone without intervening zones of shale. The Upper Cambrian sandstones in Wisconsin grade southward through dolomitic sandstone and sandy dolomite into dominant dolomite, again without gradation through a zone of shale.

The evaporite basin enclosed within its biohermal ring is typified by examples in the Michigan basin during Silurian and Devonian. The arkose wedge in the south-central part of the map area is characteristic of the Fountain arkose (Pennsylvanian) along the Front Range. The Fountain arkose grades northward into

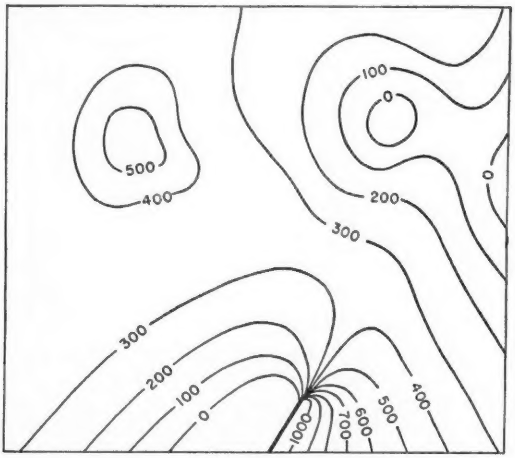

FIG. 6.—Cycle of deposition, VI. Isopachs of deposits formed during major cycle.

quartzose sandstone, so that a gradation from arkose to quartzose sand may occur rapidly in nature. The occurrence of continental shales grading into lagoonal and marine shales, with linear beaches, is typical of the Cherokee section of eastern Oklahoma, in the rich Bartlesville producing areas. These shoestrings, according to Bass (1936) represent barrier beaches along a lagoon-fringed Cherokee sea.

Toward the close of the hypothetical cycle of deposition, the tectonism of the area diminishes in intensity, with the result that the higher land surfaces are reduced to an erosional base level, and the sediments washed into the sea are distributed in accordance with a base level adjusted to wave and current base. The closing deposits in the region will thus be a veneer of widespread shelf sediments over the entire depositional area, possibly with culminating evaporites in the biohermal ring. At the instant that the depositional cycle may be considered closed, that is, just before withdrawal of the sea, the thickness of the sediments show a pattern much like that in Figure 6. The isopachs indicate a few areas of

non-deposition during the cycle, in the higher parts of the old landmasses; and thick deposits in the intracratonic basins, with the major thickness in the arkose wedge immediately east of the normal fault. Over much of the broad shelf area the sediments are relatively uniform in thickness. Hence, the isopachs at that moment reflect the general tectonism which prevailed during the depositional cycle. Figure 7 shows a northwest-southeast cross section through the hypothetical map area at the close of the cycle of deposition.

If the succeeding cycle of deposition occurs without significant subaerial exposure, then the entire stratigraphic interval will be preserved under cover, with its isopach pattern intact. More commonly, perhaps, an interval of erosion occurs between major depositional cycles, which results in the stripping away of parts

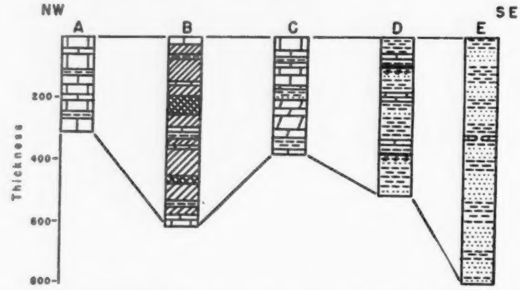

FIG. 7.—Cycle of deposition, VII. Stratigraphic section from fusulinid limestone (NW) to to sand-shale basin (SE) of Figure 5.

of the previously deposited material. If warping occurs in the shelf area, parts of the deposit may be entirely removed by erosion. Nevertheless, the important fact remains that the preserved remnants of sediment still retain their lithologic and biological characteristics, despite the fact that the isopach pattern is modified by the erosion. Hence, from the preserved remnants a more or less complete picture of environments and tectonic activity may be reconstructed.

APPLICATIONS OF TECTONO-ENVIRONMENTAL CLASSIFICATION

It is implied in the preceding treatment of the hypothetical example that the pattern of organic and depositional environments and of tectonic behavior remained relatively fixed during the time required for the deposition of a three-dimensional mass of sediments. Therefore, at any point of observation of the resulting column of sediment, nearly uniform response to environment and prevailing tectonism may be traced through vertically successive layers of sediment. That is to say, the biologic, lithologic, and tectonic aspect at any point is the result of a single dominant condition. This is illustrated in Figure 7, which represents a stratigraphic section from northwest to southeast in Figure 5. Column A shows mainly fusulinid limestone, with minor clay shale breaks, characteristic

of infraneritic conditions on a stable shelf. Column B represents the evaporite section of the northwest restricted basin, with thin limestones and dolomites, and a few thin shales. Column C is typical of the limestone area southeast of the evaporite basin, and shows normal marine and fossiliferous-fragmental limestones and their dolomitized equivalents with a few clay shales or thin quartzose sandstones. Column D represents the cyclical deposits of the unstable shelf; and ranges from non-marine subgraywacke sands, underclays, and coal, to thin marine limestones and thicker marine to brackish shales. Column E occurs in the transition area between arkose and basin shales in the southeastern part of Figure 5, and has mainly arkosic to subgraywacke sands, and silty shales, with thin nodular limestones.

Each of the sections reflects the persistence of a dominant environmental and tectonic condition, except for column D, which lies in the transition zone of mild instability, and hence reflects an alternation of continental and marine environments. In actual examples the persistence of environmental and tectonic patterns may not normally maintain, and the rock column at any point commonly reflects vertically successive responses to shifting environments and tectonic states.

Analysis of these more complex situations requires methods for differentiating and expressing the changing biologic, lithologic, and tectonic influences on the section. The writers (Sloss, Krumbein, and Dapples, 1949) have previously applied the terms biotope, lithotope, and tectotope to the rock record of biologic, lithologic, and tectonic influences. The use of these terms may be illustrated with an actual example. Figure 8 is a stratigraphic section of several lower Des Moines cyclothems from western Illinois. The column at the left indicates the lithotopes present (kinds of lithology). The biotopes (beds or units having similar faunal assemblages) are not indicated, but in general they coincide with the lithotopes in this section. The central column indicates the inferred environmental conditions in which the sediments accumulated. The lower beds in the cyclothems are placed in a combined fluvial-lacustrine-swamp environmental group; and the upper shales and limestones are interpreted in terms of brackish and marine neritic conditions. The last column shows the grouping of tectotopes (beds or units representing similar tectonic conditions or rates of subsidence). The tectotopes are all shelf types, and represent the range from essentially stable conditions during the accumulation of coal and underclay in the non-marine part of the cyclothem and of limestone in the marine part; to more rapid subsidence during the deposition of the subgraywacke sandstones. The over-all tectonic aspect is that of an oscillating shelf area, with positive movements indicated by disconformities in other parts of the complete section.

The lithotopes, biotopes, and tectotopes of any section may be expressed in terms of the over-all lithologic, biologic, and tectonic aspect which they display; and these characteristics may be used as a basis for preparing lithofacies, biofacies, and tectofacies maps (Krumbein, 1948; Sloss, Krumbein, Dapples, 1949). In the same manner, the environments represented in the section may be ex-

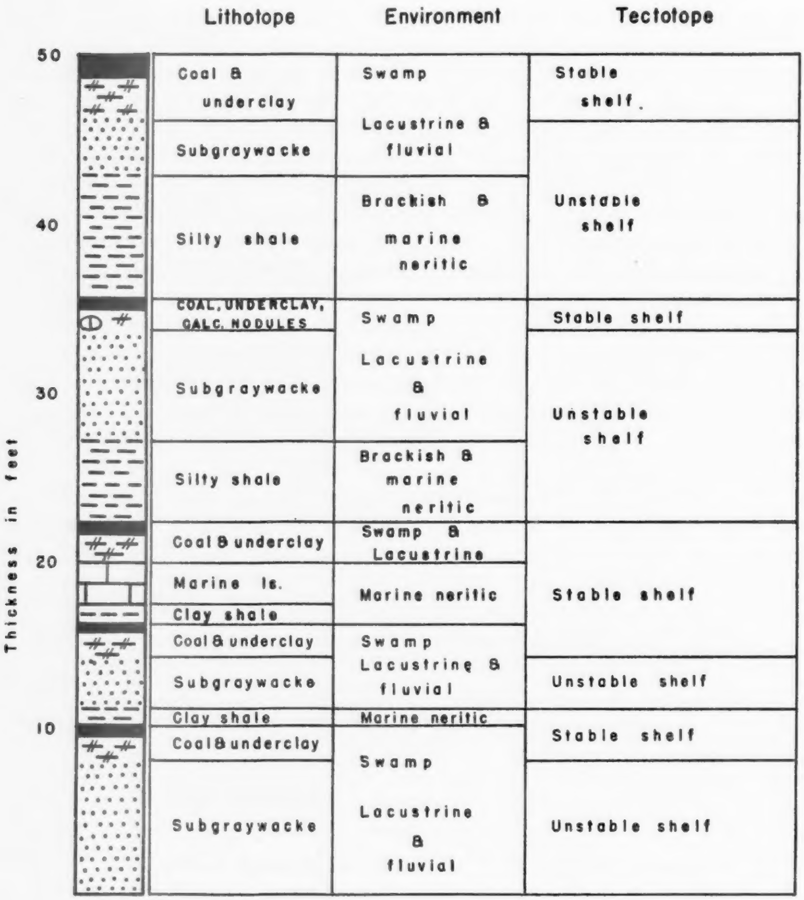

FIG. 8.—Analysis of part of Desmoinesian in western Illinois, in terms of lithotopes tectotopes, and environmental groups.

pressed in any of several ways to denote the over-all environmental aspect of the section. Thus, the section in Figure 8 may be expressed in broad terms as transitional continental-marine, with a dominance of non-marine conditions; or the ratio of marine plus brackish beds to continental beds may be computed, yielding the value 0.51 in the illustrative example. More simply, the per cent of marine plus brackish beds may be stated as 34 per cent of the section.

Analysis of sections of a stratigraphic unit in the manner indicated may be used as the basis for environmental maps, which display the areal variation in

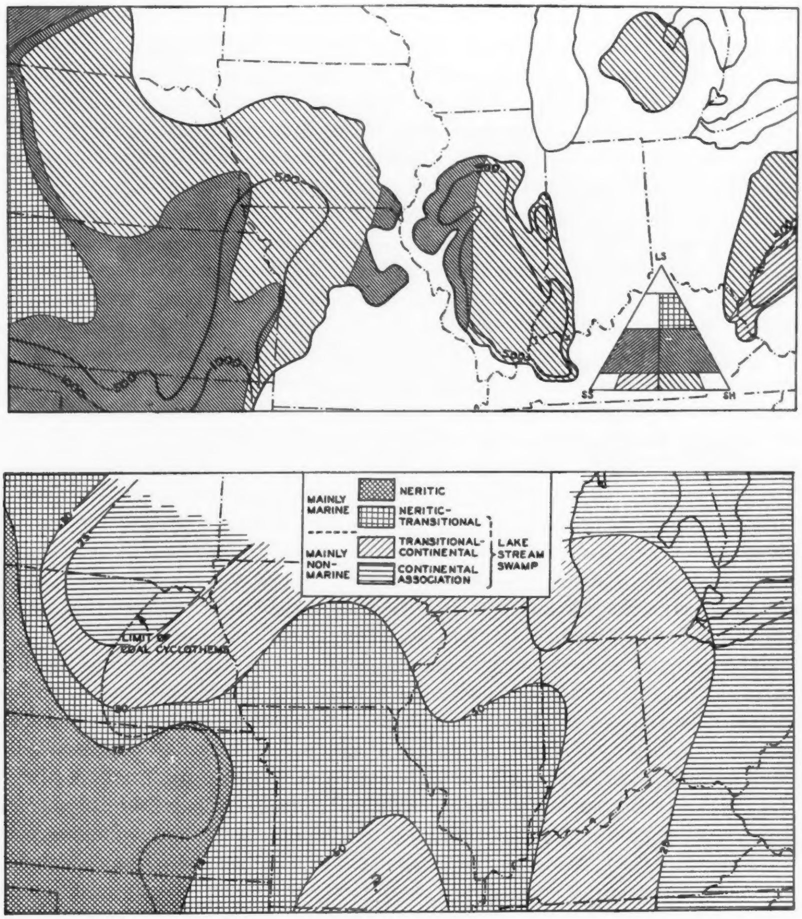

FIG. 9.—Experimental map of Desmoinesian Stage. *Top*, statistical lithologic groups; *bottom*, distribution of generalized environmental conditions.

gross environmental aspect of the stratigraphic unit. Reference to the figures illustrating the hypothetical cycle of deposition show that Figure 5 is the lithofacies map, Figure 4 is the biofacies map, Figure 2 is the tectofacies map, and Figure 3 is the environmental map.

As an illustration of an actual instance, experimental maps were prepared of the Desmoinesian Stage, from western Kansas to Pennsylvania. Inasmuch as cyclothems occur over much of the area, the data were assembled in the manner

indicated in Figure 8, by analyzing such stratigraphic sections as were available with adequate faunal and detailed lithologic data. The first stage was the preparation of a lithofacies map based on the clastic ratio and sand-shale ratio (Krumbein, 1948). This map is shown in the upper part of Figure 9. The data were then re-expressed in terms of the proportion of marine beds in the section, and a second map (lower map of Figure 9) was prepared to show the broad pattern of environmental associations.

In western Kansas the Desmoinesian is a lime-shale section, consisting of more than 50 per cent shelf-type limestones, with light to dark shales, also dominantly shelf types. Sandstone is subordinate, and is mainly fine-grained quartzose sandstone. All beds are marine, with both epineritic and infraneritic faunas represented. The dominant environment is marine neritic, with a representation of epineritic conditions. Eastward, in central Kansas, the section becomes shale-limestone, with the shale exceeding the limestone. Occasional brackish shales and thin coals attest to interruptions in the continuous occupation of the area by the sea. The line of 75 per cent marine beds in part parallels the limit of prominent coal-bearing cyclothems, but in the northwest the marine line appears to swing through western Nebraska and into South Dakota, beyond the limit of well developed cyclothems. In northern Nebraska and eastern South Dakota, the occurrence of red sediments in a shale-sand section, and a generally non-marine aspect, suggests that marine conditions may not have formed as much as 25 per cent of the beds. The lack of detailed information on the writers' part in this area renders the present interpretation of that area only tentative.

Over most of the coal-cyclothem area between eastern Kansas and Indiana, the section is shale-sand or locally shale-limestone. Marine beds exceed continental. The proportion of marine beds decreases northward, and there is some evidence in Missouri that the proportion of marine beds may also have been lower over parts of the Ozark uplift. In Ohio and West Virginia, and perhaps also in Michigan, the proportion of marine beds in the section apparently drops below 25 per cent, resulting in a dominantly continental assemblage; and in West Virginia the section becomes mainly sand-shale. The broad environmental relations are indicated on the regional environmental map by classifying the areas with less than 25 per cent marine beds as a continental association, made up mainly of fluvial, lacustrine, and swamp environments. The areas between 25 and 50 per cent marine beds are designated as transitional continental, as shown on the map legend. Areas with more than 50 per cent marine beds are grouped into neritic transitional and dominant neritic.

On the assumption that the Desmoinesian lithofacies and environmental maps are correct to a first approximation, there are several interesting implications which arise in the historical geology of that stratigraphic unit. One gains the impression that the terrane receiving sediments must have been very nearly featureless over its entirety, so that relatively slight changes in sea-level moved the strand line across extensive areas. The sea continuously occupied the fairly stable

shelf of western and central Kansas, sending broad sheets of marine waters eastward and northeastward during the negative phases of repeated oscillations of the shelf farther east. The waters withdrew as positive movements occurred, or as sediments in the eastern part of the area accumulated above sea-level forcing the strand westward. Tectonic influences increased generally eastward, as shown by the thickened sub-units in the Forest City and Illinois intracratonic basins, as well as the thickening section toward the Appalachian geosyncline. These areas, by virtue of their relatively greater subsidence during negative parts of the oscillations, acquired a correspondingly greater amount of sediment to maintain baselevel conditions. This general picture of invasion of the seas from the west agrees with recent paleogeographic maps, such as in Moore (1949, p. 201).

The inference is strong that the main source of sediments for the eastern half of the area was at the east, assumably in active orogenic elements in the Appalachian geosynclinal belt. The shales of the Anadarko basin, the edge of which is shown on the southern margin of the map, assumably came from orogenically active areas along the Amarillo-Arbuckle-Wichita trend. The quartzose Tensleep sandstone beyond the extreme northwestern part of the map area, and the relatively thin sediments in South Dakota and Nebraska, may have been derived largely from the Shield area or the Sioux uplift. Similarly, at least part of the Forest City and Illinois basin sediments were derived from the north. Thus, it appears that several source areas supplied sediment to the Desmoinesian some of which were intracratonic positives, and others were associated with geosynclinal belts. This general picture agrees with Moore and Thompson's recent (1949) reconsideration of Pennsylvanian classification. The Oklan series, of which the Desmoinesian is the upper stage, follows an interval of disturbance along the main geosynclinal belts at the close of Ardian time. During the Atokan (lower stage of the Oklan) tectonic influence was marked, and resulted in the accumulation of thick basin shales in negative intracratonic areas. During the ensuing Desmoinesian the tectonic framework of sedimentation became largely a shelf area, with greatly reduced negative tendency in former basin areas. However, the source areas of the Atokan continued to yield sediments during the Desmoinesian.

CONCLUDING REMARKS

The inherently great difficulty of interpreting and mapping environments of ancient sediments depends in part on the superposition of tectonism upon environmental influences. Ordinarily the tectonic influence is longer-lived for any area than is a single environment. As a result, it is usually necessary to observe a succession of environments within a stratigraphic unit set in its larger framework of tectonism. The environmental aspect is thus seen, as it were, through a glass tinted by tectonism. The distorting or blurring effect of the tectonism varies with its intensity, somewhat in the manner suggested in Figure 10. Along the

vertical axis are shown typical environmental groups of sediments, ranging from deep marine to continental. The horizontal axis is a scale of tectonic intensity, shown as logarithmic to suggest the greatly increasing effects of tectonic activity. The shaded zones in the diagram illustrate the manner in which the environmental picture is clouded by increasing tectonic intensity. Perhaps the most sensitive part of the environmental picture is the transitional zone, which responds immediately to strand-line shifts, and hence results in maximum interfingering, gradation, and intertonguing of deposits The figure suggests that even in relatively stable areas it may be difficult to locate exact strand lines; and as tectonic intensity increases, the clouding effect extends to environmental groups on both sides of the transitional environment. This clouding increases in importance as

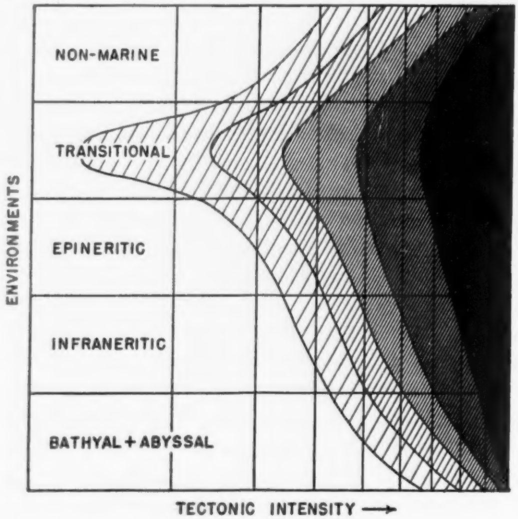

FIG. 10.—Diagram showing inferred clouding effect of contemporaneous tectonism on environmental reconstruction of stratigraphic unit.

tectonism reaches higher stages of intensity, until in very mobile geosynclinal belts it may be difficult if not impossible to discern and distinguish the extremes of continental and marine.

Despite the clouding of environmental reconstruction by increasing tectonism, it is possible in many instances to discern the environment, provided a suitable means is available for expressing environmental characteristics in mappable units. The techniques suggested are probably suitable for regional studies, but require considerable sharpening for detailed studies of thinner intervals in limited areas. As the diagram of Figure 10 suggests, most success in recognizing the environment may be anticipated in areas of low tectonic intensity, which extend

from stable shelf deposits to those of intracratonic basins. As understanding of the influence of tectonism increases, and as methods of expressing average or dominant environment progress, one may anticipate increasingly satisfactory methods of isolating and defining the environmental implications of stratigraphic units.

It is also apparent that in general both sedimentary tectonics and sedimentary environment operate simultaneously to give the section its over-all characteristics; and that instead of being mutually exclusive concepts, tectonics and environment are complementary, and operate hand in hand in the development of a body of sedimentary deposit.

REFERENCES

BARRELL, J., "Rhythms and the Measurements of Geologic Time," *Bull. Geol. Soc. America*, Vol. 28 (1917), pp. 745–904.

BASS, N. W., "Origin of Shoestring Sands of Greenwood and Butler Counties," *Univ. Kansas Bull. 23*, (1936).

DAPPLES, E. C., KRUMBEIN, W. C., AND SLOSS, L. L., "Tectonic Control of Lithologic Associations," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 32 (1948), pp. 1924–47.

ELIAS, M. K., "Depth of Deposition of the Big Blue (Late Paleozoic) Sediments in Kansas," *Bull. Geol. Soc. America*, Vol. 48 (1937), pp. 403–32.

FLEMING, R. H., AND REVELLE, R., "Physical Processes in the Ocean," *Recent Marine Sediments*, Amer. Assoc. Petrol. Geol. (1939).

KAY, M., "Paleogeologic and Palinspastic Maps," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 29 (1945), pp. 426–50.

KING, P. B., "Permian of West Texas and Southeastern New Mexico," *ibid.*, Vol. 26 (1942), pp. 533–736.

KRUMBEIN, W. C., "Criteria for Subsurface Recognition of Unconformities," *ibid.*, pp. 36–62.

——— "Lithofacies Maps and Regional Sedimentary-Stratigraphic Analysis," *ibid.*, Vol. 32 (1948), pp. 1909–23.

LEE, W., "Stratigraphy and Structural Development of the Forest City Basin in Kansas," *Kansas Geol. Survey Bull. 51* (1943).

MCCOY, A. W., "An Interpretation of Local Structural Development in Mid-Continent Areas Associated with Deposits of Petroleum," *Problems of Petroleum Geology*, Amer. Assoc. Petrol. Geol. (1934), pp. 581–628.

MOORE, R. C., "Environment of Pennsylvanian Life in North America," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), pp. 459–87.

——— *Introduction to Historical Geology*. McGraw-Hill, New York (1949).

——— AND THOMPSON, M. L., "Main Divisions of Pennsylvanian Period and System," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 33 (1949), pp. 275–302.

PETTIJOHN, F. J., *Sedimentary Rocks*, p. 442. New York (1949).

SCOTT, G., "Paleoecological Factors Controlling the Distribution and Mode of Life of Cretaceous Ammonoids in the Texas Area," *Jour. Paleon.*, Vol. 14 (1940), pp. 299–323.

SLOSS, L. L., KRUMBEIN, W. C., AND DAPPLES, E. C., "Integrated Facies Analysis," *Geol. Soc. America Memoir 39* (1949), pp. 91–123.

TERCIER, J., "Depots marins actuels et series geologiques," *Eclogae Geologicae Helvetiae*, Vol. 32 (1940), pp. 47–100.

WILSON, I. F., "Buried Topography, Initial Structures, and Sedimentation in Santa Rosalía Area, Baja California, Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 32 (1948), pp. 1762–1807.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 33, NO. 11 (NOVEMBER, 1949), PP. 1892-1900, 1 FIG., 3 TABLES

STATISTICAL STUDY OF ACCURACY OF SOME CONNATE-WATER RESISTIVITY DETERMINATIONS MADE FROM SELF-POTENTIAL LOG DATA[1]

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ABSTRACT

A statistical comparison between 39 connate-water resistivities computed from S.P. (self-potential) electrical logs and the comparable measured resistivities has demonstrated the usefulness as well as the limitations of the method of calculation proposed by the writer. The data on which this study was based were 34 routine Schlumberger electrical surveys made in oil fields in Illinois, Oklahoma, and Kentucky.

It is shown that the theoretical interpretation of the electrochemical e.m.f. (electromotive force) will give, on the average, the correct connate-water resistivities only for S.P. kicks which refer to thick and relatively low resistant formations and ones which have little shale interbedding. In the case of S.P. kicks which are grossly pointed or very serrated the connate-water resistivities computed are, on the average, somewhat too high.

A significant correlation has been found between the magnitude of the errors of interpretation and the resistivities of the Aquagel muds used in the logging. The errors are not significantly dependent on the salinity of the connate waters in the formations studied.

The McClosky producing zone gives rise to abnormally low computed resistivities, but no satisfactory explanation of this phenomenon has yet been found.

INTRODUCTION

It has been shown elsewhere (1) by the writer that in electrical logging where the predominant cation in both the connate water of a formation and the fluid in the borehole is sodium, the maximum electrochemical S.P. kick can be fairly accurately expressed in terms of the salinities of the two fluids by the following expression.

$$E = 2.303 \frac{RT}{F} \left(1 + \frac{u-v}{u+v} \right) \log \frac{a_c}{a_m} \qquad (1)$$

where E = electrochemical e.m.f.
R = gas constant per mole
T = absolute temperature
F = Faraday
u = mobility of cation
v = mobility of anion (assumed to be chloride)
a_c = activity of sodium chloride in the connate water
a_m = activity of sodium chloride in the borehole fluid

It was also shown that at low connate-water salinities the activity ratio a_c/a_m could be replaced, as an approximation, by the ratio of the resistivities of the borehole fluid and connate-water. For connate-water salinities in excess of about 60,000 mg./liter as sodium chloride, it was pointed out that this approximation led to increasing errors, and for high connate-water salinities it was necessary to

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[2] Electrochemist, Gulf Research and Development Company. The writer is indebted to A. C. Godbold and his assistants for their work in collating logs and formation water data and making the information available to him. The writer's thanks for permission to publish this paper are due to Paul D. Foote, executive vice-president, Gulf Research and Development Company.

use the activity ratio. The mean activity coefficients for sodium chloride which were used to compute the sodium chloride activities were taken from Latimer (2).

By using equation 1 and the method of computing sodium chloride activities described, connate-water salinities and resistivities have been calculated from routine electrical logs. If such salinities and resistivities can be computed with reasonable accuracy, equation 1 and the quantitative theory of the electrochemical S.P. component to which it gives form are essentially correct.

DATA

The Tulsa division of the Gulf Oil Corporation made available 48 Schlumberger electrical logs which had been run in Gulf wells during 1945, 1946, and 1947. These logs referred to wells in oil fields in the states of Illinois, Kentucky and Oklahoma, and analyses were furnished of typical produced formation water from sands in each of these fields.

TABLE I

RESULTS CONSIDERED RELIABLE FROM VISUAL INSPECTION OF LOGS

Well	*Pool*	*Location*	*Formation*	*Mud Resis. 18°C.*	*Salinity (Milligrams Per Liter)*		*Resistivity (18°C.)*		*% Error*	*Remarks*
					Calculated	*Measured*	*Calculated*	*Measured*		
Green 3	W. Divide	Jefferson, Ill.	Cypress	2.2	132,000	120,000	0.078	0.086	− 9	Salinity estimated
Gabriel 2	S. Stanford	Clay, Ill.	Cypress	3.0	130,000	132,000	0.079	0.078	+ 1	
Gabriel 1	S. Stanford	Clay, Ill.	Cypress	3.0	72,000	120,000	0.125	0.086	+45	Salinity estimated
Pittman 1	S. Stanford	Clay, Ill.	Tar Springs	2.6	110,000	120,000	0.09	0.086	+ 5	Salinity estimated
Lorance 1	Markham City W.	Jefferson, Ill.	Aux Vases	2.9	142,000	140,572	0.073	0.074	− 1	
Nora 3	Keenville	Wayne, Ill.	Cypress	3.8	120,000	135,000	0.084	0.077	+ 9	Salinity estimated
Peterson 3	Markham City W.	Jefferson, Ill.	Tar Springs	3.3	135,000	145,000	0.077	0.075	+ 3	
Raburn 1	Markham City N.	Wayne, Ill.	Cypress	1.9	200,000	150,000	0.058	0.070	−17	
Cotcha 9	Little River	Seminole, Okla.	L. Cromwell	3.8	120,000	135,847	0.084	0.077	+ 9	
Remaklus 4	Garcreek	Seminole, Okla.	Gilcrease	1.2	195,000	172,350	0.058	0.064	− 9	Good kick but close to T.D.
Hunt 1	S. Sylvian	Seminole, Okla.	Cromwell	1.9	145,000	171,236	0.073	0.065	+12	
Cotcha 20	Little River	Seminole, Okla.	L. Cromwell	2.3	130,000	135,847−	0.078	0.077	+ 1	
Lucy 2	Cheyraha	Seminole, Okla.	Booch	3.0	170,000	170,481	0.065	0.065	0	
Rankin 24	Powells Lake	Union, Ky.	Mansfield	4.7	32,000	26,262	0.24	0.28	−14	Pointed kick but same as adjacent thick sands
Rankin 11	Powells Lake	Union, Ky.	Mansfield	2.9	26,500	26,262	0.28	0.28	0	Same as above
Rankin 10	Powells Lake	Union, Ky.	Mansfield	3.3	20,000	26,262	0.355	0.28	+27	Same as above
Rankin 9	Powells Lake	Union, Ky.	Mansfield	6.0	12,500	26,262	0.54	0.28	+93	
Marshall 12	Burbank Chapel	Henderson, Ky.	Cypress	6.5	108,000	100,000	0.09	0.097	− 7	
Inez Rhea 5	Uniontown	Union, Ky.	Waltersburg	3.4	49,500	50,713	0.169	0.165	+ 2	
Rhea 4	Uniontown	Union, Ky.	Waltersburg	2.1	51,000	51,000	0.164	0.164	0	

Not all of the 48 logs could be used, and 14 were discarded for the following reasons: three, because the mud resistivity on the log heading was unaccompanied by the temperature of measurement, and 11 because the formations for which water analyses were available were either poorly developed or were at total depth, that is, the well had only been drilled into the top, and not through, the formation of interest and the S.P. kick was thus indeterminate. Some McClosky producing zones were not computed because their S.P. kicks were grossly pointed and obviously not fully developed.

However, from the 34 logs which gave moderately good S.P. kicks opposite

formations for which the connate-water salinities were known, 39 connate-water salinities were computed, that is, in certain wells, as shown in the Tables I and II, the connate-water salinity of more than one formation was calculated.

The 39 S.P. kicks corresponding with the formations investigated were not all equally suitable for quantitative interpretation, since many were sharp and pointed and others gave strong indication that the formations to which they referred were considerably interbedded with shales. Both sharp S.P. kicks and kicks showing shale interbedding indicate a high probability that the measured S.Ps. will be significantly smaller than the true electrochemical e.m.fs. of the appropriate shale cells (3). These kicks will thus give connate-water salinities which are too low and connate-water resistivities which are too high. Thus it was

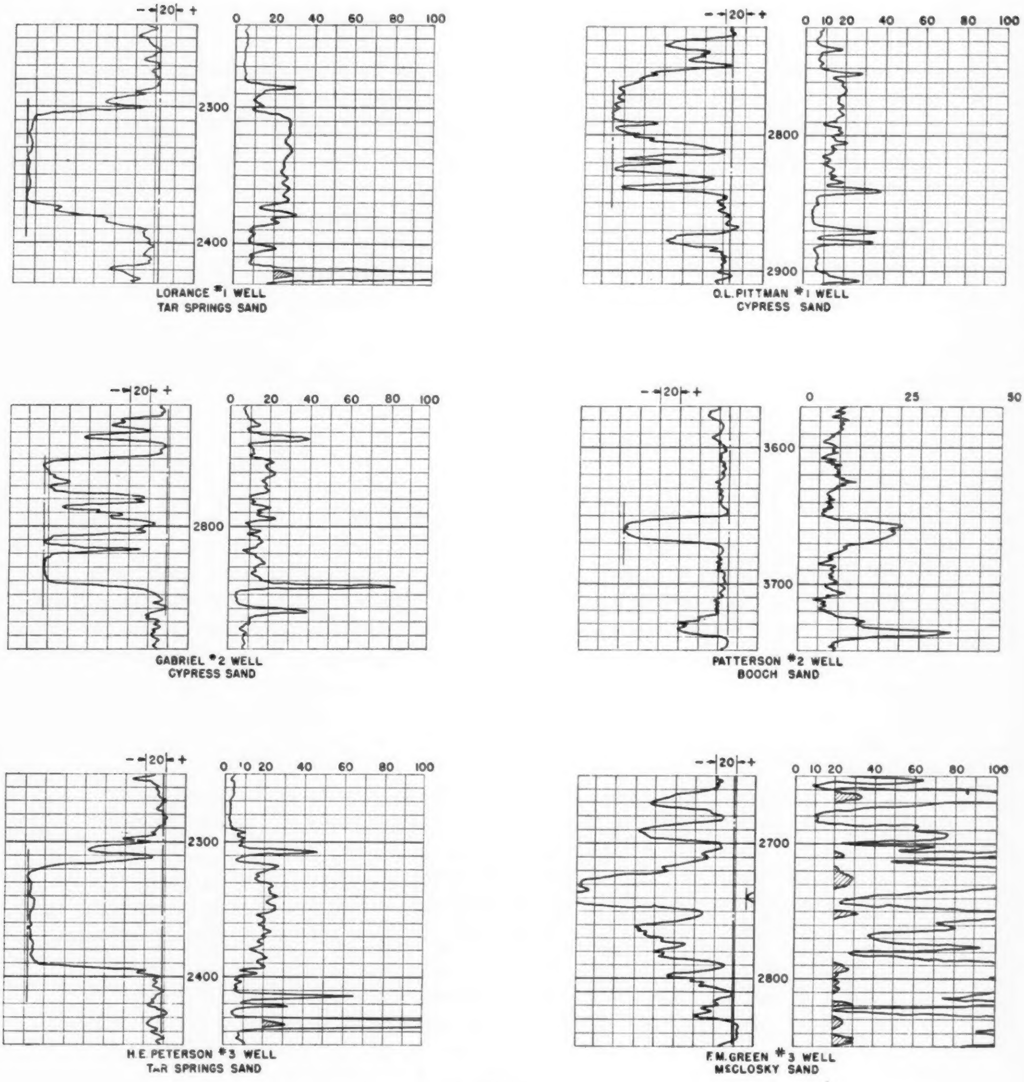
TABLE II

RESULTS CONSIDERED UNRELIABLE FROM VISUAL INSPECTION OF LOGS

Well	Pool	Location	Formation	Salinity (Milligrams Per Liter)		Resistivity (18°C.)		% Error	Remarks
				Calculated	Measured	Calculated	Measured		
Green 3	W. Divide	Jefferson, Ill.	McClosky	310,000	131,149	0.043	0.078	− 45	Pointed S.P.
Pittman 3	S. Stanford	Clay, Ill.	Aux Vases	143,000	133,332	0.073	0.077	− 5	Kick is near T.D.
Pittman 3	S. Stanford	Clay, Ill.	Cypress	83,000	120,000	0.11	0.086	+ 29	Pointed; lower than adjacent sands and Tar Springs
Pittman 1	S. Stanford	Clay, Ill.	Cypress	110,000	120,000	0.09	0.086	+ 5	Pointed and slightly interbedded
Green 1	Divide	Jefferson, Ill.	McClosky	175,000	131,149	0.064	0.078	− 18	Kick near T.D.
Alva Mays 1	Boyd	Jefferson, Ill.	Benoist	77,000	121,578	0.118	0.083	+ 42	Pointed and interbedded
Gabriel 3	S. Stanford	Clay, Ill.	Aux Vases	120,000	134,000	0.084	0.072	+ 17	Pointed and interbedded
Remaklus 2	Garcreek	Seminole, Okla.	Booch	120,000	170,000	0.084	0.065	+ 29	Pointed S.P.
Roberts 1	Cheyraha	Seminole, Okla.	Booch	140,000	170,000	0.074	0.065	+ 14	
Hulwa 4	Cheyraha	Seminole, Okla.	Booch	210,000	170,000	0.056	0.065	− 14	Pointed S.P.; poor base line
Cotcha 14	Little River	Seminole, Okla.	U. Cromwell	110,000	135,847	0.090	0.075	+ 20	Pointed S.P.; interbedded
Patterson 2	Garcreek	Seminole, Okla.	Booch	85,000	170,481	1.09	0.065	+ 68	Pointed kick but moderately good
Patterson 2	Garcreek	Seminole, Okla.	Cromwell	112,000	171,238	0.088	0.065	+ 35	Same as above
Hunt 6	E. Haney	Seminole, Okla.	Booch	110,000	171,000	0.09	0.065	+ 38	Pointed S.P.
Hunt 2	S. Sylvian	Seminole, Okla.	Booch	60,000	171,000	0.143	0.065	+120	Interbedded; otherwise good
Remaklus 1	Garcreek	Seminole, Okla.	Gilcrease	110,000	171,000	0.088	0.065	+ 35	Kick low; was corrected
Rankin 17	Powells Lake	Henderson, Ky.	Waltersburg	35,000	60,112	0.22	0.143	+ 54	Very pointed S.P.
Marshall 2	Burbank Chapel	Henderson, Ky.	McClosky	250,000	110,000	0.0498	0.09	− 44	Pointed S.P.
Rankin 12	Powells Lake	Union, Ky.	Tar Springs	46,000	60,948	0.178	0.142	+ 25	Pointed S.P.; interbedded

considered advisable to divide the 39 results into two sections, Tables I and II. In Table I are 20 results based on S.P. kicks which appear from simple inspection to be reliable, that is, the kicks refer to formations which are reasonably thick and of low resistivity and the kicks themselves have a flat top. Examples of these kicks are shown in Figure 1.

In Table II are 19 results which refer to kicks which are pointed, which are measured from poorly defined shale base lines, or which refer to formations clearly showing shale interbedding. The reliability of these results varies since a rather sharp, pointed S.P. kick may be sensibly the theoretical e.m.f. of the shale cell or may be considerably smaller, and at present there is no reliable method of assessing the error. The same is true for a moderate amount of shale interbedding in a thick sand. Examples of these kicks are also shown in Figure 1.



(a) FIG. 1 (b)

(a) VISUALLY SATISFACTORY S.P. KICKS

(b) UNSATISFACTORY S.P. KICKS

All the logs were run in Aquagel muds, excepting Rankin No. 9 which had Supergel in the hole.

Examples of formation water analyses made by the Tulsa division are given in Table III. It will be appreciated that these analyses are typical of formations in the various fields and it is probable that some variation occurs in any sand from

TABLE III

SOME TYPICAL WATER ANALYSES

State *Field* *Sand*	*Oklahoma* *Little River* *Cromwell*	*Oklahoma* *Garcreek* *Gilcrease*	*Illinois* *Bible Grove* *Cypress*	*Illinois* *Bible Grove* *McClosky*	*Kentucky* *Powells Lake* *Mansfield*	*Kentucky* *Uniontown* *Waltersburg*
Na	41,334	51,506	44,126	45,607	9,775	18,485
Ca	8,420	12,252	3,504	6,820	134	372
Mg	1,882	1,896	1,201	1,818	169	625
SO_4	100	80	nil	460	trace	400
Cl	83,940	106,480	77,649	87,230	15,266	30,482
HCO_3	171	136	146	197	918	348
Total solids	135,847	172,350	126,626	142,132	26,262	50,713
Specific gravity	1.104	1.125	1.088	1.101	1.021	1.040

Analyses in mg./liter

well to well in the same field. However, normally such differences should not introduce serious errors. Where the analysis of the water in a particular formation was not available, the computed salinity and resistivity have been compared with the mean value of the same quantities in the same formation in adjacent fields. For such formations as the Cypress and Tar Springs in Illinois this is probably justifiable.

METHOD OF CALCULATION OF SALINITIES AND RESISTIVITIES

The S.P. kicks were measured from the shale base line in the usual manner and the corresponding ratio of the connate-water activity to the mud activity (based on NaCl solutions) was found from curves (1, Fig. 1) The formation temperature used was derived either from bottom-hole temperatures when they were available on the logs, from the literature, or by assuming a reasonable temperature gradient in the hole. Errors from the use of incorrect formation temperatures are probably small.

The mud resistivity was then assumed to depend solely on sodium chloride in solution, and from a computed curve the equivalent sodium chloride activity of the mud was found. This value multiplied by the previously determined activity ratio gave the sodium chloride activity of the connate water. The use of a curve then converted the connate-water activity to mg./liter sodium chloride and also gave the connate-water resistivity at 18°C., a temperature used as a comparative standard in this work. The curves used were computed by the method described in the Introduction.

In Tables I and II the computed salinities have been compared with the measured values or the best estimates of the measured values obtained as previously described. The resistivities computed and those measured at 18°C. (based on the total solids in mg./liter being NaCl) are also shown. Since the computed values are of significance in the quantitative analysis of the log for connate-water saturation, a column showing percentage of error between the computed and measured resistivities as a percentage of the measured value is included in the tables.

It should be remembered when assessing these errors that a zero percentage error is likely to coincidental. Even if all the log data were perfectly accurate there are many unavoidable errors and approximations in the computation of the connate-water salinities. Also, the scales of the activity and resistivity curves can not be read with perfect precision, and the treatment of the measured total solids in the formation waters as pure sodium chloride is an added unavoidable approximation. It should be recollected also that the possible errors could be many hundreds per cent if the computed salinities were either very low or very high.

STATISTICAL ANALYSIS OF RESULTS

The object of the statistical methods used was to determine whether or not the errors between computed and measured resistivities were significantly different from zero. In particular, it was of interest to find whether the errors were greater for the results in Table II (as was suspected from a simple visual inspection of the logs) than for those in Table I (which from present knowledge would be assumed to be fairly reliable).

A second object was to ascertain whether there was any correlation between the errors in Table I and the true connate-water resistivities, or between the errors and the resistivities of the Aquagel muds used.

The second object arises from theoretical considerations. It is known that membrane potentials of the type apparently operative in shales are affected by the concentrations of the solutions which the membranes separate. In particular, the potential across the membrane becomes less than the theoretical Nernst potential if the concentration of one of the solutions becomes very high. Since the connate-water resistivity depends on its solute concentration, a correlation between error and resistivity might indicate a concentration effect.

Errors possibly due to the resistivities of the Aquagel muds used arise, first, from the assumption that the resistivities of these muds result wholly from the conduction effects of such simple electrolytes as sodium chloride, sulphate, carbonate, or bicarbonate. At moderate mud resistivities this is approximately true, since the dissociation of sodium ions from the clay micelles of the Aquagel is suppressed by the comparatively high concentration of sodium ions resulting from other dissolved sodium salts. At high mud resistivities, however, the clay micelles may provide a very significant percentage of the total sodium ion

A. Standard Deviation, Mean and Median for Results in Tables I and II

All 39 results obtained were first considered.

Number of results	39
Mean error	14.23%
Median error	9%
Standard deviation	31.97%

Calculation shows that the statistic t is equal to 2.74. For 38° of freedom t should be 2.028 or less if the mean error is not to be significantly different from zero. Since the t obtained is greater than 2.028 it follows that the mean error is definitely greater than zero, that is, the average calculated resistivity for these 39 results is too high, or, what is the same thing, the average salinities are too low.

B. Standard Deviation, Mean and Median for Results in Table I

Number of results	20
Mean error	7.5%
Median error	1%
Standard deviation	23.79%

Calculation shows that the statistic t is equal to 1.38. For 19° of freedom if t is less than 2.093 the mean value is not significantly different from zero. Since the calculated t is less than 2.093, for the 20 results considered the mean error is essentially zero.

C. Standard Deviation, Mean and Median for Results in Table II

Number of results	19
Mean error	21.3%
Median error	25%
Standard deviation	37.4%

Calculation shows the statistic t is equal to 2.39. For 18° of freedom if t is not less than 2.101 the mean is significantly different from zero. Since the calculated t exceeds 2.101 the mean is significantly different from zero and the mean of the 19 results in Table II is, therefore, significantly greater than zero. As would be expected from A and B, the 19 results in Table II on the average show a salinity which is definitely too low.

D. Determination of Coefficient of Correlation between Errors and Measured Connate-Water Resistivities for Results in Table I

By calculation the coefficient of correlation, r, is found to be 0.3772. For the number of results available r must be as big or bigger than 0.444 if the correlation is to differ significantly from zero. Since the calculated r is less than 0.444, there is no significant correlation between the errors and the connate-water resistivities.

E. Determination of Coefficient of Correlation between Errors and Aquagel Mud Resistivities for Results in Table I

By calculation the coefficient of correlation, r, is found to be 0.456. For the number of results available r must be as big or bigger than 0.444 for the correlation to differ significantly from zero. Since the calculated r exceeds 0.444, there is a significant correlation between the errors and the resistivities of Aquagel muds.

activity of the mud (4) and the normal assumption that the sodium ion activity results from sodium chloride or other sodium salts is seriously in error. A high resistivity Aquagel mud is in its electrochemical effects equivalent to a sodium chloride solution of considerably lower resistivity. A second analogous effect in the case of high-resistivity Aquagel muds is that the cationic activity of the mud filtrate may differ from that of the mud. The assumption that the mud filter cake separates fluids of the same activity thus becomes invalid and a potential may be set up across the filter cake itself. This potential is a consequence of the fact that the mud filter cake may possess some of the electrochemical character-

istics of a shale. If the activity of the mud is greater than that of its filtrate this filter cake potential will slightly increase the magnitude of the total electrochemical e.m.f. Consequently, a correlation between error and mud resistivity might indicate that these effects were significantly affecting the results obtained.

The statistical criteria calculated are here presented. These are based on standard statistical tables (5).

CONCLUSIONS

Statistical analysis of 39 computed salinities composed of 20 results which a visual inspection of the log would indicate as being reliable, and 19 which a visual inspection would reject as unreliable, shows the following.

1. The interpretation of good S.P. kicks with flat tops corresponding with sands which do not show heavy shale interbedding will give, on the average, connate-water resistivities which are essentially correct, and these conditions may be estimated visually from the log.

2. The quantitative theoretical interpretation of the electrochemical e.m.f. is reasonably satisfactory.

3. Calculations based on S.P. kicks which are pointed or which indicate shale interbedding in the formation will show, on the average, high connate-water resistivities. This means that good results can not be expected for thin beds.

4. The agreement between calculated and measured connate-water resistivities does not appear to depend significantly on the concentration of the brine in the connate water for concentrations of total solids up to approximately 170,000 mg./liter.

5. For Aquagel muds, there is a significant degree of correlation between the mud resistivity and the magnitude of the error between calculated and measured connate-water resistivities.

The agreement between measured and calculated resistivities is generally satisfactory and even the 19 results considered unreliable show salinities of the right order of magnitude. One serious anomaly was noted which has not been brought out fully in either Table I or II. The McClosky producing zone shows errors of -44%, -45%, and -18% in Table II. These results were for pointed S.P. kicks. Other McClosky kicks, not reported, were so excessively pointed as to be manifestly lower than the maximum theoretical S.P. However, the magnitude of some of these very pointed S.P. kicks was more than 200 m.v. and it is clear that the computed salinities would be in excess of 400,000 mg./liter. No McClosky analysis exceeds 147,279 mg./liter, and the salinity of the McClosky is nearly constant at this or lower values. The analyses of the McClosky waters show calcium and magnesium ion contents higher than in the other formation waters, but as now known the presence of these ions in solution would not be solely responsible for the abnormally high S.P. values recorded.

A significant amount of potassium or other alkali cation if present with the

sodium, would lead to sodium chloride salinities which were too high, but the error appears to be too large for this explanation even if all the sodium present was actually potassium.

The anomalous McClosky S.P. values may indicate that a streaming potential of approximately 40 m.v. is being superimposed on the electrochemical potential, or it may mean the presence of other and as yet unrecognized forms of electrochemical potential. The available data do not permit definite elucidation of this point.

REFERENCES

1. WYLLIE, M. R. J., "A Quantitative Analysis of the Electrochemical Component of the S. P. Curve," *A.I.M.E. Jour. Petrol. Tech.*, Vol. 1, No. 1 (January, 1949), Tech. Paper Section, pp. 17–26; see pp. 18–20. *Tech. Pub. 2511*.
2. LATIMER, W. M., *Oxidation Potentials*, p. 325. Prentice-Hall, New York (1938).
3. DOLL, H. G., "The S. P. Log, Theoretical Analysis and Principles of Interpretation," *A.I.M.E. Petrol. Tech.* (September, 1948). *Tech. Pub. 2463*. 40 pp.; see pp. 10–12.
4. MARSHALL, C. E., AND KRINBILL, C. A., "The Clays as Colloidal Electrolytes," *Jour. Phys. Chem.*, Vol. 46 (1942), pp. 1077–90.
5. FISHER, R. A., *Statistical Methods for Biological Agricultural and Medical Research*, pp. 26 and 36. Oliver and Boyd, London (1938).

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 33, NO. 11 (NOVEMBER, 1949), PP. 1901-1903, 1 FIG.

GEOLOGICAL NOTES

OVERLAP AND NON-CONFORMITY[1]

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There has been considerable discussion on the confusion which exists in geological nomenclature concerning distinction between overlap and the somewhat similar appearing truncation of regularly inclined strata beneath an unconformably overlying younger stratum.[3] Actually there is no genetic similarity between the two phenomena, and the structural similarity is not real.

Overlap is properly applied to the relation between a series of beds (or strata), within a conformable series, where, successively, each younger bed extends beyond the edge of the next older bed and so overlaps the latter. This relation may occur (and commonly does occur) at a surface of unconformity where, as deposition progresses, the thickening formation encroaches on the old erosion surface; but association with a surface of unconformity is not essential in the definition. Overlap may be transgressive or regressive, and it may be developed in sedimentation which is marine, or lacustrine, or terrestrial. Without exception, there is a connotation of imbricating layers, younger layers covering and extending beyond the edges of older layers, and in a certain way, also, there is an included connotation of this process as progressive.

The relation of *truncation* is very different. Here one layer or formation lies unconformably (non-conformably) on the bevelled edges of a series of older eroded layers. There is no overlap in the sense of progressive imbrication—progressive in time as well as in place. The overlying formation covers the older series *en masse*, and the false appearance of overlap in the older series is not at all overlap in the sense of younger beds lapping over the edges of older beds.

These two features of true overlap and truncation of inclined beds below a non-conformity are so completely different—genetically and structurally—that we believe any attempt to bring them both under one classification or under the same group name is illogical and ill-advised. They should be kept distinct, and if some new term is sought for the second feature as here described (truncation), it should neither imply, nor refer to, overlap. This word, overlap, should be restricted to the group of features which it correctly describes, although within its scope there may be special variety names, such as onlap (transgressive overlap) and offlap (regressive overlap).

[1] Manuscript received, September 2, 1949.

[2] Geological and research counselor, Sun Oil Company.

[3] Frank A. Melton, "Onlap and Strike-Overlap," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 31, No. 10 (October, 1947), pp. 1868–78; H. R. Lovely and Frank A. Melton, "Onlap and Strike-Overlap," *ibid.*, Vol. 32, No. 12 (December, 1948), pp. 2295–97.

MINIATURE STADIA ROD: A TEACHING AID[1]

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Miniature stadia rods, small-scale replicas of ordinary rods, are useful in teaching field-geology students how to operate on alidade. The tiny rods permit

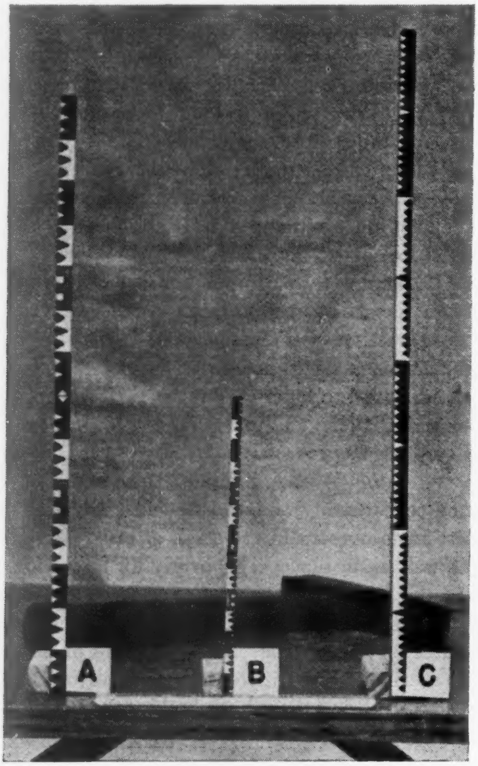

FIG. 1.—Miniature stadia rods.

A. Scale is one-twelfth of regular 14-foot rod, 0.33 inch wide, 14 inches long. One inch represents one foot.

B. Scale is one-twenty-fourth of regular 14-foot rod, 0.17 inch wide, 7 inches long. One-half inch represents one foot.

C. Scale is one-tenth of international 4-meter rod, 0.8 centimeter wide, 40 centimeters long. 10 centimeters represent one meter.

[1] Manuscript received, September 26, 1949.

[2] Department of geology, University of Texas. For valuable discussions on this subject appreciation is expressed to G. A. Muilenburg, R. K. DeFord, A. H. Deen, H. A. Ireland, H. P. Bybee, and I. J. Anderson.

the student unlimited practice in reading the instrument without the need of a rod man. Further, the practice may be carried on indoors during inclement weather or at night. The instrument operator simply assumes that the little rod he sees through the instrument is a full-scale rod and all calculations and map plotting are made in a normal way. The rods may be set up in the laboratory by the instructor to cover all of the various techniques applying to plane-table and alidade operation. Most important, the instructor may give quizzes on instrument reading, requiring every student to have mastery of the methods. Such quizzes eliminate the problem created by students who deliberately avoid their turn at the instrument for an easier task in the field of holding the rod. The use of miniature rods is a supplement to, and not a substitute for, regular field instrument training.

The writer does not know who originated the idea of miniature rods and he is not aware of any literature on the subject. Certainly, the idea is not new because tiny rods are known to have been in use at least 10 years ago at the University of Missouri, Columbia, Missouri, and the University of Missouri School of Mines and Metallurgy, Rolla, Missouri. The rods were introduced in the University of Texas Tertiary field course in 1949.

The model rods used by the writer at the University of Missouri School of Mines and Metallurgy and at the University of Texas were drafted on drawing paper. The paper was trimmed and glued to a piece of wood of proper size. This was then attached to a suitable support or base so that the rod would stand vertically. The most convenient scale employed was one-twelfth the size of a standard rod. As shown in Figure 1, this rod is 0.33 inch wide, 14 inches long, and made so that one inch represents one foot. For practice on long distance shots and for use in small rooms a scale of one-twenty-fourth the size of a standard rod was used. A replica of a 4-meter rod was constructed to a scale one-tenth the size of a regular rod for the purpose of giving practice to those students planning to do instrument work abroad. In selecting rod patterns the suggestions outlined by Cox, Dake, and Muilenburg[3] for greater visibility range were adopted.

[3] G. H. Cox, C. L. Dake, and G. A. Muilenburg, *Field Methods in Petroleum Geology*, pp. 71–75. McGraw-Hill Book Company, New York (1921).

EXPLORATORY DRILLING IN NORTH CAROLINA IN 1946[1]

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"Exploratory Drilling in 1946," published in the June number of this *Bulletin* in 1947, failed to include six dry exploratory holes, all new-field wildcats, with a total of 30,182 feet, drilled in 1946 in North Carolina.

[1] Manuscript received, November 1, 1949.
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DISCUSSION

NAMES OF SOME SUBSURFACE STRATIGRAPHIC UNITS IN TEXAS[1]

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In general the subsurface paleontologist and stratigrapher will approve the recommendations made in Note 4 of the American Commission on Stratigraphic Nomenclature.[3] The writer is inclined to doubt, however, the accuracy of the statement in item 4: "that subsurface formations now are studied and analyzed with a degree of precision that was impossible fifteen years ago."

It is believed that in the Gulf Coast province the aggregate length of the cores now taken is much less than it was before the widespread use of the electric log. That a new tool, however useful, has been permitted to replace other sources of information rather than supplement them is regrettable. It is true that cores now taken are subjected to a scrutiny much more exhaustive than in the past, but from the engineering rather than the stratigraphic viewpoint. In fact, the laboratory worker on subsurface geology may never receive any portions of reservoir cores. The use of shaker cuttings for foraminiferal study, rather than the old type ditch samples also reduces the number of foraminifera found, because the possible microfossil content of sands and easily slaking claystones are now largely lost to the laboratory worker.

Also, objection is made to part of item 11 of the Note in which the current usage of the term Frio in the subsurface is cited as illustrating the desirability of renaming a surface unit because of the inaccurate application of its name to a subsurface unit. It may well be that the usage of Frio in the subsurface is now so widespread and firmly established in the literature that it must be maintained. The objectionable part of item 11 is the statement that no one has seen fit to try to correct the inaccurate application of the term Frio in the subsurface. This statement ignores two published protests against this erroneous application. Alexander Deussen and Kenneth Dale Owen,[4] about ten years ago, recognized that the outcrop Frio and the subsurface "Frio sand" (p. 1617) are not equivalent. This is shown on their two cross sections (Figs. 2 and 3), on their diagrammatic sections (Figs. 5 and 6), and in Table I, p. 1633. Further, they showed the subsurface "Frio," the "Middle Oligocene" marine wedge, and the reduced Catahoula of the subsurface as all being equivalent to the Catahoula tuff or Gueydan of the outcrop. They suggested that the name "Van Vleck sands" be used for the subsurface unit, rather than "Frio." They also suggested names and type localities for the marine wedge member and the sands above the marine wedge. Their excellent suggestions seem to have been ignored by most later workers. While the preceding paper was in press, a second[5] was written, reaching nearly the same conclusions.

[1] Manuscript received, March, 1949. Published by permission of the director of the United States Geological Survey.

[2] United States Geological Survey. Division of Geological Sciences, California Institute of Technology.

[3] Wayne V. Jones and Raymond C. Moore, "Naming of Subsurface Stratigraphic Units," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 32, No. 3 (March, 1948), pp. 367–71.

[4] Alexander Deussen and Kenneth Dale Owen, "Correlation of Surface and Subsurface Formations in Two Typical Sections of the Gulf Coast of Texas," *ibid.*, Vol. 23, No. 11 (November, 1939), pp. 1603–34.

[5] M. C. Israelsky, "Notes on the Frio," *ibid.*, Vol. 24, No. 2 (February, 1940), pp. 377–82.

Shortly thereafter, Phil F. Martyn and Charles H. Sample,[6] for the first time, clearly defined the Frio in its present popular usage. The Frio as thus defined is a part of Dumble's original Frio;[7] hence, there can be no legalistic objections to such restriction. The East White Point field would thus provide the type section of the Frio according to the plan for establishing subsurface type sections set forth in item 11. It is interesting to note Martyn's change from an earlier point of view.[8] Accepting the Frio in its redefined sense, correlations with surface outcrops show it to be part of T. L. Bailey's[9] Gueydan, or the Catahoula tuff. This tuffaceous group seems to be the equivalent of the Catahoula sandstone of Louisiana, the type locality for the Catahoula. The Catahoula, in its downdip occurrence both in Louisiana and Texas, is split by a marine wedge which was formerly called the "Middle Marine Oligocene" but has now been termed the Anahuac formation.[10] Thus, in effect, these two lithologic units, Frio (redefined) and Anahuac are removed from the unit originally called Catahoula, and in common practice only that part of it lying above the Anahuac is referred to as Catahoula in the subsurface. If we extend the thesis that general subsurface usage must be accepted, it seems that the outcrop Catahoula of Louisiana must also be redefined.

It is also desired to consider briefly the current subsurface usage of two other names, Cockfield and Hackberry, and some implications arising therefrom. Yegua and Cockfield are names originally applied to equivalent surface lithologic units, mappable one into the other, from Texas to Louisiana. This seems to be generally accepted.

About 1930, laboratory reports appeared listing "Cockfield forams" as occurring above "Yegua forams." This unfortunate usage of Cockfield spread rapidly among the commercial laboratories and soon appeared in the literature,[11] all without formal explanation of the neologism.

In 1934, however, Hanna and Gravell correctly placed the *Nonionella* zone in the Yegua, and with this the writer concurred in 1935.[12] Later in 1935, he stated that "The Cockfield formation of the Louisiana outcrop and the adjacent and equivalent Yegua of northeast Texas from which *Nonionella cockfieldensis* was described are essentially deltaic deposits having their inception in late Claiborne time and continuing into Jackson time."[13] The usage of Cockfield for a subsurface unit overlying Yegua still continues.[14]

[6] Phil F. Martyn and Charles H. Sample, "Oligocene Stratigraphy of East White Point Field, San Patricio and Nueces Counties, Texas," *ibid.*, Vol. 25, No. 11 (November, 1941), pp. 1967–2009.

[7] M. C. Israelsky, *op. cit.*, p. 377.

[8] E. H. Finch, P. F. Martyn, O. G. Bell and R. F. Schoolfield, "Yeager Clay," *ibid.*, Vol. 15, No. 8 (August, 1931), pp. 967–70.

[9] M. C. Israelsky, *op. cit.*, p. 377.

[10] Alva C. Ellisor, "Anahuac Formation," *ibid.*, Vol. 28, No. 9 (September, 1944), pp. 1355–75.

[11] Alexander Deussen, "Oil-Producing Horizons of Gulf Coast in Texas and Louisiana," *ibid.*, Vol. 18, No. 4 (April, 1934), pp. 500–18; Table I, p. 501. Cockfield (*Nonionella cockfieldensis* zone) is used as a subdivision of the Yegua.

[12] Roy T. Hazzard and B. W. Blanpied, "Guidebook of the Eleventh Annual Field Trip of the Shreveport Geological Society in Southeast Mississippi" (1934), with a correlation chart by Hanna and Gravell, reproduced in the following reference.

Merle C. Israelsky, Review of "Guidebook of the Eleventh Annual Field Trip of the Shreveport Geological Society in Southeast Mississippi," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19, No. 4 (April, 1935), pp. 571–75.

[13] Merle C. Israelsky, "Tentative Foraminiferal Zonation of Subsurface Claiborne of Texas and Louisiana," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19, No. 5 (May, 1935), p. 690.

[14] W. L. Goldston, Jr., and George D. Stevens, "Esperson Dome, Liberty County, Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 18, No. 12 (December, 1934), pp. 1632–54. On p. 1640 Cockfield and Yegua are termed members, the first lying on the second, as illustrated in Figs. 4 and 5.

Selwyn O. Burford, "Structural Features of Brenham Salt Dome, Washington and Austin

The truth is that the Yegua-Cockfield lithologic sequence straddles the line between the Jackson and Claiborne faunal divisions, or, in other words, includes the final offlap of the Claiborne and the onlap of the Jackson. Outside Texas, Cockfield continues to be used as the equivalent of the Yegua, not as a subdivision thereof.

It seems that "Cockfield" as used in the subsurface of Texas is as much in need of reconsideration as "Frio."

Perhaps with "Hackberry," we may yet be forehanded. The term "Hackberry" was applied to a foraminiferal assemblage[15] lying below that of the Anahuac and above the Vicksburg, and was meant simply to denote that the first recorded occurrence of the assemblage was on the Hackberry dome. It was not meant to have either time or lithologic significance. Yet it is regularly being so used in the subsurface departments of numerous companies, and unless the practice is stopped, one foresees "Hackberry" creeping into the literature in a formational sense. This is to be deplored as the name "Hackberry" is several times preoccupied.[16] The "Hackberry" is mainly claystone, the downdip equivalent of the abbreviated "Frio," of current subsurface usage, and is deserving of a name.

Obviously there will always be difficulty in achieving complete standardization of the names of stratigraphic units. The foregoing review of some peculiarities of current usage in the subsurface of Texas suggests that this is true even when there is no essential disagreement about the correlations of the units involved. It also suggests the need for caution in so revising the standards of stratigraphic nomenclature as to grant subsurface units equivalent standing to surface units, until it is more evident that full and accurate usage has been made of the surface nomenclature available.

Counties, Texas," *ibid.*, Vol. 19, No. 9 (September, 1935), pp. 1330–38. Cross section (Fig. 2 shows Cockfield as a member of the Yegua formation.

Alexander Deussen, and E. W. K. Andrau, "Orange, Texas Oil Field," *ibid.*, Vol. 20, No. 5 (May, 1936), pp. 531–59. In section on p. 540, Cockfield is used as a formation in the Yegua group.

Frank W. Michaux, Jr., and E. O. Buck, "Conroe Oil Field, Montgomery County, Texas," *ibid.*, Vol. 20, No. 5 (May, 1936), pp. 736–79. Cockfield used as a member of the Yegua formation (Fig. 2 on p. 742, and p. 745).

Herschel H. Cooper, "Occurrence and Accumulation of Oil in Laredo District, Texas," *ibid.*, Vol. 21, No. 11 (November, 1937), pp. 1422–38. Cockfield used as a formation overlying the Yegua formation (p. 1426).

Alexander Deussen, and Kenneth Dale Owen, "Correlation of Surface and Subsurface Formations in Two Typical Sections of the Gulf Coast of Texas," *ibid.*, Vol. 23, No. 11 (November, 1939), pp. 1603–34. Cockfield used as the upper member of the Yegua (p. 1609, Figs. 2 and 3).

Harvey Whitaker, "Hoffman Field, Duval County, Texas," *ibid.*, Vol. 24, No. 12 (December, 1940), pp. 2126–42. Cockfield used as a formation overlying the Yegua formation (Table I, p. 2129).

R. L. Beckelhymer, "Stratigraphy of Waller and Harris Counties, Texas," *ibid.*, Vol. 30, No. 1 (January, 1946), pp. 52–62. Cockfield used as the upper member of the Yegua formation (Fig. 2, p. 55; p. 59).

A. P. Allison *et al.*, "Geology of Katy field, Waller, Harris, and Fort Bend Counties, Texas," *ibid.*, Vol. 30, No. 2 (February, 1946), pp. 157–80. Cockfield used as the upper member of the Yegua formation (p. 165, Fig. 38, p. 167).

[15] J. B. Garrett, "The 'Hackberry' Assemblage—An Interesting Foraminiferal Fauna of Post-Vicksburg Age from Deep Wells in the Gulf Coast," *Jour. Paleon.*, Vol. 12, No. 4 (1938), pp. 309–17.

[16] M. Grace Wilmarth, "Lexicon of Geologic Names of the United States," *U. S. Geol. Survey Bull. 896*, Pt. 1 (1938), pp. 893–94.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 33, NO. 11 (NOVEMBER, 1949), PP. 1907-1913

REVIEWS AND NEW PUBLICATIONS

* Subjects indicated by asterisk are in the Association library, and are available, for loan, to members and associates.

GUIDEBOOK, FOURTH ANNUAL FIELD CONFERENCE, POWDER RIVER BASIN, WYOMING, 1949, BY WYOMING GEOLOGICAL ASSOCIATION

REVIEW BY PHILIP W. REINHART[1]
Casper, Wyoming

**Guidebook, Fourth Annual Field Conference, Powder River Basin, August 9–13, 1949*, by Wyoming Geological Association. 102 pp., 23 geologic, structural, and facies maps, including three large, folded maps; 4 index maps; 9 geologic columnar sections, including one with radioactivity log; 7 stratigraphic correlation charts, including 2 large, electric-log charts; 5 pages of photographs; 8 geophysical maps (7 gravimeter and 1 magnetometer); 1 physiographic diagram; 1 oil-field penetration chart; 1 geophysical activity diagram; 1 geologic map index and bibliography. Heavy paper cover, plastic, wide-opening binder, 8.5×11 inches. Published and sold by the Wyoming Geological Association, Box 545, Casper, Wyoming. Price, $5.00, prepaid.

Published in connection with the Wyoming Geological Association's Fourth Annual Field Conference, this guidebook not only served its purpose admirably during the conference, as road log and reference manual, but has already won assurance of a place of permanent usefulness in the working library of everyone concerned with the geology and oil development of Wyoming. The committee, under whose able guidance the conference was organized and the guidebook published, consisted of the following: G. W. Berry, general chairman; Page T. Jenkins, guidebook editor; H. D. Hand, road log editor; J. F. Fouts, accommodations; George L. Goodin, registration; Frank A. Morgan, Jr., caravan; Victor H. King, advertising.

The *Road Logs of Scheduled Trips* describe in detail the 490 miles of highway and dirt road traversed by the conference caravan during the three field days, covering the entire west flank of the Powder River Basin from the Montana state line to Casper, 150 miles south. The road logs are illustrated with geologic sketch maps, structure sections, and stratigraphic charts. Variety and interest are added by the appendage of notes on frontier-day history and folk-lore, including a fabulous account of the exploits of the Lake De Smet Monster. The *Exit Road Logs*, included for the purpose of adding interest to automobile trips elsewhere in the basin than along the route covered by the conference, describe the geology along most of the commonly traveled roads throughout the interior and eastern margin of the basin, totalling 781 miles. A *Flight Log* of the Powder River Basin was prepared in connection with an airplane trip, taken on the final day of the conference, which covered a circular route of more than 500 miles around the entire Wyoming part of the basin.

Approximately two-thirds of the book is devoted to papers on regional geology and on oil fields. The *Papers on Regional Geology* include two on structure, two on stratigraphy, one on gravitational and magnetic exploration, and one on photogeological analysis. The following is a list of titles in this category: "Structural Pattern of the Powder River Basin," by D. L. Blackstone, Jr.; "Structure of the Tongue River Area, Big Horn Mountains, Wyoming," by Frank W. Osterwald; "Summary of Paleozoic Stratigraphy of the Powder

[1] Senior geologist, Shell Oil Company. Review received, September 20, 1949.

River Basin," by Horace D. Thomas; "Mesozoic Rocks of the Northern Powder River Basin, Wyoming," by George R. Downs; "A Discussion of the Application of the Gravitational and Magnetic Methods of Exploration to the Powder River Basin," by Willis H. Fenwick; and "Methods of Photogeologic Evaluation in a Tertiary Basin," by Laurence Brundall.

Blackstone's paper encompasses the structure of the entire basin, in Montana as well as Wyoming, building up the concept of the whole by discussion of successive parts of the basin. Particular emphasis is laid on the western margin which, because of its relative complexity, is of greater structural interest than the eastern part. Of considerable interest is the discussion of the relation between the steepness of the Big Horn mountain front and the development of folds along the adjacent basin margin. In Osterwald's paper, attention is focused on a relatively small area (approximately 150 square miles) of pre-Cambrian and Paleozoic rocks along the crest of the northern part of the Big Horn Mountains. By mapping dip and strike observations on planar foliation in granite, the author worked out a large north-northwest plunging "syncline" in these rocks which has a trend in general similar to the trend of the Big Horn Mountains. Shear zones in the granite, which outline a rectangular, block-like pattern, are described. After comparing the structural features of the pre-Cambrian rocks with those of the Paleozoic strata, the author concludes in part, that

> Laramide deformation along these pre-Cambrian structural features has produced folding and faulting of Paleozoic and Mesozoic sediments, by adjustment to vertical block movements in pre-Cambrian rocks. The locus of the eastward margin of the range has probably been determined by a change to more gneissic rock types.

The first of the two papers on stratigraphy, by Thomas, describes in lucid style the more important facts concerning the composition, thickness, occurrence, and age and correlation of the various Paleozoic formations. The stratigraphy of the Cambrian, Ordovician, and Mississippian formations is relatively simple as compared with the complexities of the Pennsylvanian and Permian beds, in which important changes of facies occur. For example, the relationship of the Tensleep to the Minnelusa, Hartville, and Casper formations, in which facies changes are involved, is discussed fully and clearly. An appended correlation chart is very useful for quick reference.

The second paper on stratigraphy, by Downs, ably describes the Mesozoic formations in detail, discussing their distribution, thickness, composition, environmental conditions of deposition, and age and correlation. The confusing array of formational names in current usage on the west and east sides, respectively, of the basin is brought to order in the discussion and by means of a detailed correlation chart.

The paper by Fenwick, on gravimeter and magnetometer exploration, is a very clear, informative discussion which fairly brings out the weak as well as the strong points of the methods dealt with. It was written specifically for the geologist with little or no knowledge of geophysics, and in simple language describes the various factors which enter into application and interpretation of gravimeter and magnetometer surveys. For this reason, it will be welcomed by those who normally recoil from pages bristling with mathematical formulas. In essence, the application of these methods to oil exploration is based on analogy; known structural features around the rims of the basin have been surveyed and contoured, and exploration has been pushed out into the interior of the basin where structural conditions are not apparent, with the hope that unknown, buried structures will be similarly reflected in the contour pattern. Although gravity surveying has been successful in mapping structures in areas where Lance and older rocks are exposed at the surface, as is well illustrated by a series of total and residual gravity maps accompanying the report, the results in the Eocene-covered part of the basin have so far been inconclusive, possibly, as pointed out, because of lack of knowledge of structural conditions, which causes the

relationship between structure and gravity anomaly to remain problematical. Most of the foregoing discussion is based on gravity rather than magnetic surveys, as the amount of detailed magnetic work done in the basin is said to be comparatively negligible.

Brundall's discussion of photogeology consists of a detailed exposition of the various procedures followed by Geophoto Services, from the beginning to the end of a photogeologic mapping project. Recommended specifications for adequate photographs will be helpful to those interested in attempting photogeologic work. A scale of 1:20,000 is considered adequate for most Tertiary basin photogeologic work, and a camera with $8\frac{1}{4}$-inch focal length lens is recommended as best suited to the purpose. The limitations of the photogeologic method are discussed, and the necessity of a field check pointed out. For example, in some areas, outcrops clearly visible on the ground can not be detected in air photographs, and yet in other areas, features visible on photographs are difficult to discern on the ground. Thus photogeology, which is described as a specialized type of surface mapping, and geologic field work are mutually supplemental. Photogeology has won its place as an exploration tool by its speed and relatively low cost of coverage, which permits the intelligent selection of certain areas of anomalous structure for more detailed investigation by surface mapping or seismic work.

The following oil field papers comprise the remainder of the text of the book: "Newcastle Sandstone, Upper Cretaceous, Wyoming," by H. E. Summerford, E. E. Schieck, and T. C. Hiestand; "Résumé of the Oil and Gas Fields along the Eastern Margin of Powder River Basin, Wyoming," by William G. Dady; "Billy Creek Gas Field," by W. A. Bramlette; "Tisdale Anticline," by Ben Hudson; "Lance Creek, East Lance Creek, and Little Buck Creek Oil Fields, Niobrara County, Wyoming," by Rolland W. McCanne; "Big Muddy Oil Field, Converse County, Wyoming," by W. G. Olson; "The Salt Creek Oil Field," by R. W. Mallory; and "Production of Crude Oil and Gas in the Powder River Basin, Wyoming," compiled by Petroleum Information, Inc.

This series of papers describes in detail the geology and oil production of most of the oil and gas fields encircling the Wyoming part of the Powder River Basin. All are written by specialists, and for the most part the papers are well illustrated by maps, columnar sections, and structure sections. The Newcastle Sandstone paper gives a detailed account of the stratigraphy and structure of the producing oil zones of the Mush Creek-Skull Creek area on the east flank of the Powder River Basin. This area is of particular interest at the present time because of the recency of its development, and because it is one of the few areas of stratigraphic-trap accumulation in the Rocky Mountains. Illustrations are excellent, consisting of geological and facies maps and detailed electric-log stratigraphic cross sections.

Space does not permit a detailed discussion of the other oil field papers, although it should be pointed out that they contain a wealth of information, geological and historical. The Tisdale anticline is included in this series, even though it does not produce oil, because it is an exceptionally large structure on which approximately 30 exploratory wells have been drilled, the most recent of which was drilled into the pre-Cambrian basement. One fact stands out clearly in the review of these several papers: the Powder River Basin fields, in sharp contrast to those of the Big Horn and Wind River basins, produce most of their oil from Cretaceous and Jurassic reservoirs and—with the exception of Lance Creek—only little from the Pennsylvanian. Furthermore, although the Mississippian produces important quantities of oil elsewhere in the Rocky Mountains, it has produced almost none in the Powder River Basin as yet although it has been drilled on a number of large structures.

The production statistics for the Powder River Basin fields include for each field the discovery date, average gravity of the oil, number of wells, yearly production from time of discovery through 1948, and cumulative production. Twenty oil fields and one gas field are

included in the tabulation. Salt Creek has by far the largest cumulative production, more than 331 million barrels of oil. Next is Lance Creek, with 80 million barrels, followed by Big Muddy, with 31 million barrels. Of the remainder, 6 fields have produced 1 to 6 million barrels, 3 have produced between 100,000 and 1 million barrels, and 8 have produced less than 100,000 barrels.

Special Maps and Charts (in back pocket of book) are as follows: "Geologic Map and Structure Sections (plus stratigraphic section) of the Red Fork Powder River Area," by C. E. Carlson, covering an area extending 15 miles westward from the Kaycee anticline, in southwestern Johnson County; "Geologic Map of the Powder River Basin," by J. D. Love and J. L. Weitz, which is a preliminary edition of a part of the new U.S.G.S. map of Wyoming, now in preparation; "Correlation Chart—Northern Powder River Basin, Wyoming"; and "Correlation Chart—Southern Margin Powder River Basin, Wyoming," both by W. G. Olson *et al.*, consisting of large-scale electric-log correlation charts tying together the available deep wells in and around the margins of the basin; "Section of Rocks Exposed in Big Horn River Canyon—Hardin Area, Big Horn County, Montana," by P. W. Richards *et al.*, a detailed columnar section, graphic and written, from the Gallatin formation, Cambrian, up to the base of the Lance, Upper Cretaceous.

Altogether 41 persons are mentioned in the guidebook as having contributed their efforts specifically to its publication and to the field trips held in connection with the conference. Practicing oil geologists, for the most part resident and non-resident members of the Wyoming Geological Association, cooperated in this task, with the signal assistance of other groups, notably the geology faculty of the University of Wyoming and members of the U. S. Geological Survey, who—this year, as in the past—contributed wholeheartedly to the success of the conference and guidebook.

It is of interest to note that the first geological field conference in Wyoming—a 40-day trip by lumber wagon, starting and terminating at the University of Wyoming—was held just 50 years ago, during the summer of 1899. An account of this expedition, together with a photograph of the indefatigable participants, is to be found on the introductory pages of the guidebook.

SEARCH FOR PETROLEUM IN PORTUGAL, BY FERNANDO A. C. GONÇALVES MACIERA

REVIEW BY GLEN M. RUBY
Laguna Beach, California

*"Planificação Histórico-Cronológica das Pesquisas de Petróleo em Portugal" (Historical-Chronological Account of Search for Petroleum in Portugal), by Fernando A. C. Gonçalves Maciera, *Serviço de Fomento Mineiro Estudos, Notas e Trabalhos*, Vol. 4, Fasc. 2 (Porto, Portugal, 1949), pp. 68–164; 20 pls., 2 folded maps. Portuguese.

This work is an excellent history of oil prospecting in Portugal, beginning with the first discovery of asphalt in the year 1844. The various stages of attempts to develop commercial petroleum in the country are divided into three periods.

The first, which covers the time from the first discovery of bituminous substances to the year 1917, is a chronological account which runs familiarly parallel with the history of early prospecting in nearly all countries where the Government was the sole agency in dictating the terms of the concession.

It was not until 1904 that a concessionnaire was permitted to dig or drill deeper than 40 meters. However, it is not likely that this regulation was much of a handicap, since, in the early days, only open pits were used for mining the several hundred tons of asphalt which found a ready market in the country.

Since this history is concerned mostly with the various companies which were formed

to search for petroleum, as well as the gradual changes in the regulations which were designed to encourage exploration, but at the same time protect the rights of the Government from too greedy speculators, there is little mention of the geological occurrences of the various oil indications which inspired the search. There is one observation by Paul Choffat which can also apply to early geological efforts in many other places. Choffat was a Swiss geologist who spent most of his very useful life in Portugal. He, more than any other man, has been responsible for accurately classifying the sedimentary rocks and, in the early years of his field work in Portugal, he recognized the very complicated structural conditions in the vicinity of the various oil seeps, especially Torres Vedras.

Many of the early wells had been located by British and French geologists who were considered authorities in the early part of the present century, but they were reported to have spent little time in Portugal. When these wells failed to find oil, Choffat observed that "the reason was not the incompetence of the authors (of the geological reports) but the difficulties resulting from the regions studied, since they differ plenty from the rest of Europe." He also noted that they had arrived at their conclusions after very little time spent in the field.

The first period of prospecting, which failed to develop commercial petroleum, came to a close when the Legislature recognized the necessity of giving larger grants, in order to justify prospecting on a large scale.

In spite of the fact that the Government became willing to give large concessions for prospecting, there were no immediate signs of activity. This may have been due to the indefinite royalty, not less than 5 per cent, and the fact that part of the shares of any company were to be owned and voted by the Government. However, during this period, 1917 to the end of 1936, there were some accidental discoveries of gas in shallow wells, and a few occurrences of asphalt were being prospected. The Government, itself, became oil conscious and not only did some prospecting, but classified much of its land for oil and other substances.

The third phase begins on December 14, 1936, when the famous English promoter, Henry J. Pierce, on behalf of a British syndicate, asked for a large concession to explore for petroleum. On the same date, and asking for the same concession, was presented a petition by Anglo-Ecuadorian Oilfields, Ltd. This complicated matters and some delay was experienced. In the end, the Government decided to receive bids, by way of special terms and to give the concession to those making the best offer.

On July 10, 1937, the bids were opened and Pierce and his partner were adjudged to have made the best offer. After a too short period of geological work, which was seriously hampered by lack of transportation for Clive Mendelsohn, the British geologist, drilling was commenced.

Most of the activity was on the very complicated structure at Torres Vedras. All told ten wells were drilled on various fault blocks in this structure, the deepest being 1,164 meters. None of them found oil in commercial quantities, although encouraging showings were reported.

In 1947 the shares in the English company were transferred to a new company owned by the Axel Johnson interests of Sweden, and the Portuguese Government. This new company employed the New York firm of consulting geologists, Exploration Contractors, Inc., to make an extensive geological survey in order to appraise the petroleum possibilities of the region and to make locations for test wells. This work is now in progress.

RECENT PUBLICATIONS

ALABAMA-TENNESSEE

*"Pre-Cambrian and Paleozoic Rocks of Northern Alabama and South-Central Tennessee." *Guide Book, Seventh Field Trip, Mississippi Geological Society* (1949). 89 pp.,

5 pls., numerous text figs. Prepared by a committee of which Frederic F. Mellen was chairman and F. T. Holden was editor. Mississippi Geological Society, Box 2253, West Jackson, Mississippi.

APPALACHIANS

"Upper Mississippian Rocks of Southwestern Virginia, Southern West Virginia, and Eastern Kentucky," by Ralph H. Wilpolt and Douglas W. Marden. *U. S. Geol. Survey Prelim. Chart 38,* Oil and Gas Inves. Ser. (September, 1949). 3 sheets, 40×54 inches. For sale by Director, U. S. Geological Survey, Washington 25, D. C. Price, $1.00 for set of 3 sheets.

AUSTRALIA

*"Stratigraphical Nomenclature in Australia," by M. F. Glaessner, H. G. Raggatt, C. Teichert, and D. E. Thomas. *Australian Jour. Sci.*, Vol. 11, No. 1 (August, 1948), pp. 7–9. Australasian Medical Publishing Company, Ltd., Seamer and Arundel Streets, Glebe, Sydney.

*"Mesozoic Fossils from the Snake River, Central New Guinea," by M. F. Glaessner. *Memoirs Queensland Museum,* Vol. 12, Pt. 4 (May 3, 1949), pp. 165–81; 7 figs., 2 pls. A. H. Tucker, Govt. printer, Brisbane.

GENERAL

Oil! Titan of the Southwest, by Carl Coke Rister. 432 pp., illus. Foreword by E. DeGolyer. University of Oklahoma Press, Norman. Price, $5.00.

*"Interpretative Petrology of Sedimentary Rocks," by Gordon Rittenhouse. *World Oil,* Vol. 129, No. 7 (Houston, Texas, October, 1949), pp. 61–66; 10 figs

*"Radioactive and Electrical Logging," by V. J. Mercier. *Ibid.*, pp. 128–32; 2 figs.

Publications of the Geological Survey. First Supplement to Edition of May, 1948 (1949) 12 pp. Free on application to Director, Geological Survey, Washington 25, D. C.

"Preliminary Maps and Reports Released by the Geologic Division, 1946–47, and by the Conservation Division, 1938–47," compiled by Ruth A. Atherton, Wenonah H. Eckstein, and R. E. Spratt. *U. S. Geol. Survey Cir. 56* (October 14, 1949). List may be obtained without charge from Director, U. S. Geological Survey, Washington 25, D. C.

The status index maps published by the Geological Survey on a scale of 1:5,000,000, which were temporarily out of stock, have been reprinted and may again be had free on application, as follows.

"Status of Topographic Mapping in the United States" (3d ed.). Shows and classifies by color patterns all areas covered by topographic maps published by the Geological Survey and other Government agencies.

"Status of Aerial Photography in the United States" (4th ed.). Shows by color patterns or outlines the various Government agencies holding the films.

"Status of Aerial Mosaics or Photo Maps in the United States" (1st ed.). Shows by color patterns or outlines the various Government agencies holding the films.

"Status of Horizontal Control in the United States" (1st ed.). Shows by line and color pattern areas covered by triangulation and transit-traverse surveys.

"Status of Vertical Control in the United States" (1st ed.). Shows routes of all level lines reported to date.

Annual Reviews of Petroleum Technology, Vol. 8, Covering 1946 (1949). 445 pp. "The book is a complete record of 1946 developments in all sections of the industry." Includes: "Petroleum Geology," by G. D. Hobson (6 pp.); "Geophysics," by J. McG. Bruckshaw (5 pp.); "Drilling," by E. C. Scott (7 pp.); "Production," by C. J. May (10 pp.). Institute of Petroleum, 26 Portland Place, London, W. 1, England. Price, 27s 6d. ($5.50), post-free.

Seismicity of the Earth and Associated Phenomena, by B. Gutenberg and C. F. Richter.

273 pp., 34 figs., 19 tables. 8×11 inches, outside dimensions. Cloth. Princeton University Press (1949). Princeton, New Jersey. Price, $10.

*"Origin of Pimple Mounds," by E. L. Krinitzsky. *Amer. Jour. Sci.*, Vol. 247, No. 10 (New Haven, Connecticut, October, 1949), pp. 706–14; 5 pls.

KANSAS

*"Geology and Ground-Water Resources of a Part of South-Central Kansas, with Special Reference to the Wichita Municipal Water Supply," by Charles C. Williams and Stanley W. Lohman. *Kansas Geol. Survey Bull. 79* (Lawrence, July, 1949). 455 pp., 34 pls., 31 figs., 37 tables.

*"Oil and Gas Developments in Kansas during 1948," by W. A. Ver Wiebe, J. M. Jewett, and E. K. Nixon. *Kansas Geol. Survey Bull. 78* (Lawrence, Kansas, September, 1949). 186 pp., 86 figs.

MIDDLE EAST

*"Blockfolding Phenomena in the Middle East," by S. W. Tromp. *Geologie en Mijnbouw*, Vol. 11, No. 9 (September, 1949), pp. 273–78; 3 figs. In English. Editor, A. J. Pannekoek, Spaarne 17, Haarlem, Holland.

MISSOURI

*"Insoluble Residues of Some Paleozoic Formations of Missouri, Their Preparation, Characteristics and Application," by John G. Grohskopf and Earl McCracken. *Missouri Geol. Survey Rept. Inves. 10* (Rolla, 1949). 37 pp., 11 pls.

NEW YORK

*"Geologic Structures of the Lower Devonian Rocks of Central New York," by Robert E. Stevenson. *New York State Sci. Service Rept. Inves. 3* (Albany, May, 1949). 14 pp., 4 tables, 2 pls. Contains 2 pp. of addenda to "Geologic Structures of the Middle Devonian Rocks of Otsego County," *Rept. Inves. 1*, 3 pls.

PENNSYLVANIA—NEW YORK

*"Subsurface Projection of Cambro-Ordovician Sediments in the Pennsylvania-New York Region, and Relation to Oil and Gas Possibilities," by Frank M. Swartz. *Producers Monthly*, Vol. 13, No. 11 (Bradford, Pennsylvania, September, 1949), pp. 25–32; 2 figs.

TEXAS

*"Geology of the Strake and Squire Field Area, Duval County, Texas," by George G. Huffman and Alfred E. Giles. *World Oil*, Vol. 129, No. 7 (Houston, Texas, October, 1949), pp. 68–76; 1 fig.

TURKEY

*"Foraminifera from Test Wells in Adana, Turkey," by Mehlika Izgi Tasman. *Maden Tetkik ve Arama Enstitusu Yayinlarindan* (Publications of Mining Research and Exploration Institute of Turkey), Ser. B, No. 15 (Ankara, 1949). 42 pp., 6 pls. of fossils, 1 sketch map. Introduction in Turkish; abstract and text in English. Approx. 7.75×11 inches.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 33, NO. 11 (NOVEMBER, 1949), PP. 1914-1925, 8 FIGS.

THE ASSOCIATION ROUND TABLE

ASSOCIATION COMMITTEES*

EXECUTIVE COMMITTEE (1950)

C. W. TOMLINSON, *chairman*, Ardmore, Oklahoma
HENRY N. TOLER, *secretary*, Southern Natural Gas Company, Jackson, Mississippi
PAUL WEAVER, Gulf Oil Corporation, Houston, Texas
T. A. LINK, consultant, Toronto, Ontario
ALFRED H. BELL, Illinois Geological Survey, Urbana, Illinois

DIRECTORS OF AMERICAN GEOLOGICAL INSTITUTE (2-yr. term)

W. B. HEROY (Nov., 1949) PAUL WEAVER (Nov., 1950)

REPRESENTATIVE ON DIVISION OF GEOLOGY AND GEOGRAPHY NATIONAL RESEARCH COUNCIL (3-yr. term)

WALTER B. LANG (June, 1952)

REPRESENTATIVES ON COUNCIL OF AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE (2-yr. term)

W. TAYLOR THOM, JR. (Dec., 1949) ROBERT J. RIGGS (Dec., 1949)

COMMISSIONERS ON AMERICAN COMMISSION ON STRATIGRAPHIC NOMENCLATURE (3-yr. term)

W. V. JONES (Dec., 1949), *chairman* M. G. CHENEY (Dec., 1950) JOHN G. BARTRAM (Dec., 1951)

STANDING COMMITTEES

FINANCE COMMITTEE

E. O. MARKHAM (1950) JOSEPH E. POGUE (1951), *chairman* JOHN S. IVY (1952)

TRUSTEES OF REVOLVING PUBLICATION FUND

HAROLD W. HOOTS (1950) W. B. WILSON (1951)

TRUSTEES OF RESEARCH FUND

ROY R. MORSE (1950) T. S. HARRISON (1951), *chairman* HENRY C. CORTES (1952)

BUSINESS COMMITTEE

ALFRED H. BELL (1950)
E. J. BOOS (1950)
RALPH A. BRANT (1950)
C. E. BREHM (1951)
J. A. BROWN (1950)
W. Z. BURKHEAD (1951)
RALPH B. CANTRELL (1950)
FRANK B. CARTER (1950)
WALTER M. CHAPPELL (1950)
HOMER H. CHARLES (1950)
JOHN W. CLARK (1950)
W. H. CONKLING (1951)
KARL DALLMUS (1951)
MAX DAVID (1950)
D. E. EDSTROM (1951)
H. C. FERGUSON (1950)
L. E. FITTS, JR. (1951)
THOMAS J. FITZGERALD (1950)
KIRK C. FORCADE (1950)
PETER H. GARDETT (1951)
W. W. HAMMOND (1951)
DAVID C. HARRELL (1951)
JACK H. HEATHMAN (1951)
ADEN W. HUGHES (1951)
J. S. HUDNALL (1951)
HAROLD J. KLEEN (1951)
CECIL G. LALICKER (1950)
NOEL R. LAMB (1951)
T. A. LINK (1950)
WALTER K. LINK (1950)
J. B. LOVEJOY (1951)
O. G. MCCLAIN (1951)
ROBERT B. MICHELL (1950)
MARION J. MOORE (1950)
A. N. MURRAY (1951)
MANLEY L. NATLAND (1951)
R. B. NEWCOMBE (1951)
FRANK A. OYSTER (1951)
R. D. PATTERSON (1951)
VINCENT C. PERINI, JR. (1950)
W. G. PIERCE (1950)
R. DOUGLAS ROGERS (1951)
A. L. SELIG (1950)
G. J. SMITH (1951)
ALLISON J. SOLARI (1950)
R. A. STEHR (1951)
HENRYK B. STENZEL (1950)
HENRY N. TOLER (1950)
C. W. TOMLINSON (1951)
R. B. TOTTEN (1950)
D. D. UTTERBACK (1951)
C. N. VALERIUS (1951)
PAUL WEAVER (1950)
J. B. WEBB (1951)
JEROME B. WESTHEIMER (1950)
JAMES E. WILSON (1950)
BRUNO O. WINKLER (1951)

* Terms of individuals expire at close of annual meeting in April of year indicated, unless another month is shown.

COMMITTEE FOR PUBLICATION

George C. Grow, Jr. (1952), *chairman*, Peoples Natural Gas Company, Pittsburgh, Pa.

1950	1951	1952
Hollis D. Hedberg	John E. Galley	John G. Gray
G. L. Meholin	E. Russell Lloyd	Benjamin F. Hake
E. Floyd Miller	Homer A. Noble	Mason L. Hill
Vincent C. Perini, Jr.	Thomas H. Philpott	George S. Hume
Paul H. Price	Dolphe E. Simic	James A. Moore
E. E. Rehn	R. D. White	Manley Osgood, Jr.
J. K. Rogers	C. W. Wilson, Jr.	E. A. Wendlandt
K. K. Spooner		

RESEARCH COMMITTEE

John T. Rouse, Jr. (1950), *chairman*, Magnolia Petroleum Company, Dallas, Texas

1950	1951	1952
Roland F. Beers	D. L. Blackstone, Jr.	Dale L. Benson
G. C. Gester	William R. Canada	Joseph R. Clair
John T. Lonsdale	Stanley C. Herold	Ralph D. Chambers
C. V. Millikan	Walter K. Link	Parke A. Dickey
M. L. Natland, *ex. off.* SEPM	S. W. Lowman	Marcus A. Hanna
L. L. Nettleton	F. W. Rolshausen	Daniel John Jones
Paul H. Price	Robert J. Seale	Robert M. Swesnik
W. H. Twenhofel	David H. Swann	Garvin L. Taylor
Claude E. ZoBell	Georges Vorbe	

GEOLOGIC NAMES AND CORRELATIONS COMMITTEE

Henry J. Morgan, Jr. (1951), *chairman*, Atlantic Oil and Refining Company, Dallas, Texas

1950	1951	1952
C. I. Alexander	Hugh H. Beach	Charles F. Bassett
Stuart K. Clark	M. G. Cheney	George V. Cohee
W. J. Hilseweck	E. J. Combs	I. Curtis Hicks
P. H. Jennings	Robert H. Dott	Thomas C. Hiestand
Wayne V. Jones	Herman Gunter	Frederic F. Mellen
W. Armstrong Price	Raymond C. Moore	Arthur M. Meyer
H. A. Tourtelot		Grover E. Murray
		Horace G. Richards
		L. E. Workman

COMMITTEE ON APPLICATIONS OF GEOLOGY

Karl A. Mygdal (1952), *chairman*, Pure Oil Company, Chicago, Illinois

1950	1951	1952
Don L. Carroll	John B. Fanshawe	Charles A. Deegan
Stanley G. Elder	Henry D. McCallum	R. A. Stehr
Leo R. Fortier	Carl B. Richardson	
Thomas A. Hendricks	Maynard H. Steig	
W. T. Nightingale		
W. T. Schneider		

MEDAL AWARD COMMITTEE

C. W. Tomlinson, *chairman*, Ardmore, Oklahoma
H. B. Stenzel, *ex officio*, president of S.E.P.M.
Andrew Gilmour, *ex officio*, president of S.E.G.

1950	1951	1952
Frank R. Clark	Henry A. Ley	Wallace E. Pratt
Alfred H. Bell	Gordon I. Atwater	Frederic A. Bush
A. E. Brainerd	R. E. Sherrill	J. V. Howell
	H. V. Tygrett	

COMMITTEE ON STATISTICS OF EXPLORATORY DRILLING

F. H. Lahee (1950), *chairman*, Sun Oil Company, Box 2880, Dallas, Texas
Graham B. Moody (1951), *vice-chairman*, Standard Oil Co. of California, San Francisco

1950	1951	1952
Walter L. Ammon	Kenneth C. Beresford	J. A. Brown
A. H. Bell	Kenneth Cottingham	Coleman D. Hunter
Delmar O. Branson	George C. Grow, Jr.	Robert C. Lafferty, Jr
R. J. Cullen	Oscar M. Hudson	H. H. Lester
W. S. McCabe	Charles H. Row	Laurence S. Melzer
H. J. McLellan	A. N. Sharrick	D. J. Munroe
T. F. Petty	F. B. Stein	Glenn C. Sleight
R. M. Wilson	Paul Weaver	Paul H. Umbach

DISTINGUISHED LECTURE COMMITTEE

Harold T. Morley (1952), *chairman*, Stanolind Oil and Gas Company, Tulsa, Oklahoma

1950	1951	1952
John L. Ferguson	Herschel H. Cooper	H. J. Buddenhagen
W. J. Hilseweck	K. K. Landes	Robert E. Rettger
Fred H. Moore	Elliot H. Powers	
	E. E. Rehn	

SPECIAL COMMITTEES

COMMITTEE ON BOY SCOUTS LITERATURE

Frank Gouin, *chairman*, Box 208, Duncan, Oklahoma

A. C. Bace	C. L. Cooper	Ray L. Six
Max W. Ball	Carey Croneis	R. C. Spivey
H. D. Becwar	G. C. Gester	W. T. Thom, Jr.
Don L. Carroll	Don B. Gould	Russell M. Tripp
	George W. Pirtle	

COMMITTEE ON NATIONAL RESPONSIBILITY

Colonel O. F. Kotick, *chairman*, Navy Petroleum Reserves, Building T-3, Room 1046, Navy Department, Washington, D. C.

Fritz L. Aurin	Drexler Dana	William B. Heroy
Max W. Ball	Carle H. Dane	C. T. Jones
Olin G. Bell	A. Rodger Denison	C. Gill Morgan
Don L. Carroll	Ben F. Hake	W. T. Schneider
Arthur A. Curtice		Edmund M. Spieker

The Pacific Section of the American Association of Petroleum Geologists, the Society of Economic Paleontologists, and the Society of Exploration Geophysicists held their twenty-sixth annual meeting jointly at the Ambassador Hotel, Los Angeles, California, during Thursday and Friday, November 17 and 18, 1949. The annual formal dinner and dance were held on Friday evening, with dinner from 8:00 P.M. to 9:00 P.M. and dancing from 9:00 P.M. to 1:00 A.M. in the beautifully redecorated Embassy Room. Officers of the Pacific Section of the Association are: president, Clifton W. Johnson; vice-president, John E. Kilkenny; secretary-treasurer, Harold E. Rader.

Wallace L. Matjasic, *chairman*, A.A.P.G. arrangements committee
Aden W. Hughes, *president*, S.E.P.M. Charles Hewitt Dix, *vice-president*, S.E.G.

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

At the recommendation of the A.A.P.G. committee on national responsibility, in order to attain its objective "to plan and advise with the Military Services for the effective application of geology and the efficient functioning of geologists within the Military Services," the executive committee is requesting each applicant for membership to return a statement of his World War II service and his present reserve status, if any, for which purpose a special blank is furnished by Association Headquarters, Box 979, Tulsa 1, Oklahoma.

The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to the Executive Committee, Box 979, Tulsa 1, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

To comply with the new amendments affecting qualifications for membership, new applicants and their sponsors should hereafter use new (1949) application forms and the new (1949) constitution and by-laws. Old forms should be destroyed.

FOR ACTIVE MEMBERSHIP

George A. Ashland, Jr., Denver, Colo.
L. T. Hart, Horace D. Thomas, R. H. Beckwith
Philip B. Berry, Tyler, Tex.
A. B. Gross, L. E. Kennedy, Thomas W. Leach
Charles Wyatt Cargile, Shawnee, Okla.
James S. Wise, Floyd G. Kerns, A. J. Montgomery
Norman James Christie, Tulsa, Okla.
Myron C. Kiess, Paul E. Fitzgerald, L. E. Fitts, Jr.
Myles Anthony Colligan, Montebello, Calif.
Wayne M. Smith, Leo H. Moir, Jr., E. S. Pickett
Raymond V. Cruce, Bellaire, Tex.
Marcus A. Hanna, Howard Hough, W. G. Parker
David Montrose Graham, San Antonio, Tex.
Glen Petrick, Robert W. Hopf, Stanley W. Blanchard
Benjamin Rexford Hudson, Casper, Wyo.
R. E. Lindsay, Willis H. Fenwick, Allan Cree
John Edwin Husted, Midland, Tex.
John W. Skinner, Marcellus H. Stow, W. E. Cox
Grover Jim Isbell, Oklahoma City, Okla.
C. E. Yager, H. C. Vanderpool, J. J. Uri
Frans Gaspard Keyzer, Guatemala, C. A.
John F. Barrett, Richard C. Harris, H. M. Kirk
Karl Ernest Kleiber, The Hague, Holland
E. Kundig, D. Trumpy, L. E. J. Brouwer
Hugh Neil MacDonald, Chatham, Ont., Canada
W. A. Roliff, F. L. Fournier, George D. Lindberg
Holman Cannon Milhous, Nashville, Tenn.
C. W. Wilson, Jr., L. C. Glenn, Garth W. Caylor
John Albert Norwood, Barcelona, Venezuela, S. A.
George O. Relf, Jr., Henry A. Guntz, Mark F. Nero
Lloyd Dickinson Owens, Taft, Calif.
William R. Merrill, O. F. Van Beveren, John C. Wells

Frank Prudich, Albuquerque, N. Mex.
Paul H. Umbach, C. D. Johnson, B. B. Bradish
Francis Arthur Reynolds, Pasadena, Calif.
Wayne M. Smith, Leo H. Moir, Jr., E. S. Pickett
Marion R. Thomson, New Orleans, La.
Maurice J. Mayer, Jr., F. W. Rolshausen, E. P. Tatum
Tjeerd Hendrik van Andel, Wageningen, Holland
D. J. Doeglas, H. M. E. Schurmann, L. E. J. Brouwer

FOR JUNIOR MEMBERSHIP

Donald Oliver Acrey, Dallas, Tex.
Ellis W. Shuler, Kathleen S. Keathley, Claude C. Albritton, Jr.
Roy Ward Allen, Jr., Midland, Tex.
L. A. Nelson, H. E. Quinn, W. S. Strain
Voy Ernst Althaus, Fredericksburg, Tex.
Lloyd A. Nelson, H. E. Quinn, W. S. Strain
Elliott Shufflin Banta, Lewistown, Mont.
Kenneth R. Parsons, Earl G. Griffith, John E. Blixt
James Bell Bauchman, Seguin, Tex.
John R. Sandidge, F. L. Whitney, Hal P. Bybee
Kenneth Charles Beresford, Wichita Falls, Tex.
Lyman C. Dennis, D. T. Richards, Lynn L. Harden
Albert Edward Blanton, Jackson, Miss.
Frederic F. Mellen, D. C. Harrell, E. T. Monsour
Frederick H. Bockelman, Jr., Houston, Tex.
Wayne V. Jones, K. A. Schmidt, Richard T. Lyons
William Emory Bonini, Washington, D. C.
W. T. Thom, Jr., J. C. Maxwell, G. P. Woollard
James Bush, Brooklyn, N. Y.
J. J. Galloway, C. Hewitt Dix, Brooks F. Ellis
Martha Ellen Bybee, Austin, Tex.
Ronald K. DeFord, Samuel P. Ellison, Jr., G. K. Eifler, Jr.
William Richard Cook, Guthrie, Okla.
E. L. Lucas, Carl A. Moore, W. F. Cloud
George Perkins Derry, Jr., Corpus Christi, Tex.
G. R. McNutt, F. L. Whitney, G. K. Eifler, Jr.
Dwight James Edson, Jr., Houston, Tex.
Hal P. Bybee, George Sawtelle, W. A. Maley
Glenn Ernest Emmett, Vernon, Tex.
Charles A. Renfroe, W. I. Robinson, Leroy T. Patton
Daniel Bruce Flynn, Glendale, Calif.
W. C. Putnam, James Gilluly, John C. Crowell
Hugh Graham Gammell, Calgary, Alta., Canada
E. W. Shaw, D. B. Layer, W. P. Hancock
Leon Hammer, Lowell, Mass.
Kirtley F. Mather, Marland P. Billings, Winthrop P. Haynes
James Frederick Hayes, Houston, Tex.
H. B. Stenzel, Samuel P. Ellison, Jr., Irvin J. Anderson
Vincent Sloan Hefley, Jennings, La.
W. E. Belt, Jr., R. W. Wilson, C. D. Stephenson

Henry Herman Heikkila, Denver, Colo.
A. C. Waters, Siemon William Muller, A. I. Levorsen
Carl Helms, Jr., Los Angeles, Calif.
U. S. Grant, James Gilluly, John C. Crowell
William A. Jenkins, Jr., Beggs, Okla.
Hobart E. Stocking, Ray L. Six, Ralph H. Wilpolt
Charles Frances Lamb, Oshkosh, Wis.
Hal P. Bybee, G. R. McNutt, G. K. Eifler, Jr.
James Marvin Law, Shreveport, La.
Charles A. Hickcox, Claude N. Valerius, J. D. Aimer
Herbert Sylvester Mayberry, Enid, Okla.
V. E. Monnett, Leon V. Davis, Carl A. Moore
Jerry Jordan McCauley, Austin, Tex.
F. L. Whitney, Hal P. Bybee, G. R. McNutt
Dudley Richard Meier, Flushing, N. Y.
W. T. Thom, Jr., Steven K. Fox, John C. Maxwell
Gaylord O. Mickelson, Casper, Wyo.
Josiah Taylor, W. A. Kelly, W. H. Twenhofel
Edwin Thomas Murphy, Shreveport, La.
Charles A. Hickcox, Joseph Purzer, Thomas H. Philpott
Robert Edward Nelson, Boling, Tex.
S. A. Lynch, W. L. Russell, Travis J. Parker
Aubrey Leon Ott, Dallas, Tex.
Claude C. Albritton, Jr., Kathleen Keathley, Ellis W. Shuler
Othal Miles Plemmons, Olney, Tex.
Raymond Sidwell, Charles A. Renfroe, Leroy T. Patton
Erwin Jacob Poizner, Lake Charles, La.
A. C. Wright, Howard H. Lester, Leroy T. Patton
Conrad Smith Preston, Midland, Tex.
E. F. Miller, Louis Roark, Don O. Chapell
Roy Lee Pritchard, Roswell, N. Mex.
L. A. Nelson, H. E. Quinn, W. S. Strain
Stanley Earnest Pyndus, Houston, Tex.
F. L. Whitney, G. K. Eifler, Jr., Hal P. Bybee
Howard Russell Ritzma, Craig, Colo.
H. D. Thomas, D. L. Blackstone, Jr., James E. Kennan
Jack Edward Schoellhamer, Ontario, Calif.
A. O. Woodford, Merle C. Israelsky, Douglas M. Kinney
Louis Joseph Scopel, Craig, Colo.
William Beer, James W. Nance, John Theron Sanford
Fernand Joseph Souaya, Cairo, Egypt
Don L. Frizzell, H. Gordon Damon, Hal P. Bybee
James Otis Staggs, Magnolia, Ark.
L. D. Bartell, D. K. McKay, J. N. Payne
Clarence Harry Strachn, Jr., Beaumont, Tex.
G. K. Eifler, Jr., Samuel P. Ellison, Jr., Hal P. Bybee
Jack Dennis Thornton, Midland, Tex.
Raymond Sidwell, Leroy T. Patton, Charles A. Renfroe
William Everett Tipton, Dallas, Tex.
Hal P. Bybee, Samuel P. Ellison, Jr., G. K. Eifler, Jr.

Richard Hal Wesley, Detroit, Mich.
Norman S. Hinchey, Rex P. Grant, Arthur L. Jenke
Richard Allan Wetherhead, Cucuta, Colombia, S. A.
James A. Culbertson, James W. Bowler, E. Raymond Ring, Jr.
Frank Miller Whittington, Houston, Tex.
G. R. McNutt, F. L. Whitney, G. K. Eifler, Jr.
Harald Walter Woodward, Windsor, Ont., Canada
F. G. Fox, F. J. Hamilton, F. A. McKinnon

FOR ASSOCIATE MEMBERSHIP

William Lee Fellows, Caracas, Venezuela, S. A.
Verner Jones, Spence T. Taylor, Ely Mencher
Theodore Stephen Green, Tulsa, Okla.
Frank E. Brown, T. A. Clote, Thomas A. Green
John Robert Woolson, Tulsa, Okla.
Myron C. Kiess, Fred A. Devin, P. E. Fitzgerald

FOR TRANSFER TO ACTIVE MEMBERSHIP

George E. Carver, Jr., Oklahoma City, Okla.
Harold D. Jenkins, J. C. Finley, C. R. Clark
John Harrah Douglass, Corona Del Mar, Calif.
J. B. Klecker, J. H. Deming, G. W. Crickmay
Robert Louis Fienning, Duncan, Okla.
Fred A. Devin, D. M. Putman, Frank Gouin
George David Reavis, Ardmore, Okla.
Charles E. Clowe, M. P. White, Louis R. Wilson
Edward Bullock Walker, III, Barcelona, Venezuela, S. A.
Mark F. Nero, George O. Relf, Jr., George L. Lockett

NOMINEES FOR A.A.P.G. PRESIDENT, 1950–1951

C. L. MOODY

Division geologist, The Ohio Oil Co., Shreveport, La.

Born, Oct. 26, 1888, Compton, Calif.

Academic Training

1909–10	Univ. of Southern California
1912–16	Univ. of California Geology A. B., 1916
1917	Univ. of California Geology graduate student

Experience

1917–18	Consulting geologist, Casper, Wyo.
1918–	The Ohio Oil Co.

Publications.—Field of stratigraphy and structure of Rocky Mountains and Gulf Coast areas

Professional Affiliation (National)
American Assoc. Advancement of Science
Geological Society of America

A.A.P.G. Activity

1932–40	Geol. Names and Correlations Com.
1933–38	Associate Editor
1937	Vice-President
1937; 39–41; 46	Business Committee
1943–45	Trustee, Research Fund (Chm., 45)
1943–44	National Service Com.
1945	Com., Statistics Explor. Drilling
1945	Com., Method of Election of Officers
1946–47	Business Com. (Vice-Chm., 46; Chm., 47)
1947–49	Editor

THERON WASSON

Chief geologist, The Pure Oil Co., Chicago, Ill.
Born, Apr. 23, 1887, Springville, Erie Co., N. Y.

Academic Training

1907–11	Carnegie Institute of Technology B.S., School of Applied Science
1919–20	Columbia University geology

Experience

1911–13	State of New Jersey, Survey of Railroads and Canals
1913–15	Surveys and construction, oil fields of California
1915–16	New Jersey State Geological Survey
1917	Twin State Oil Company, Tulsa U. S. G. S., Topographic Br.
1920	Amer. Oil Eng. Corp., Ft. Worth
1921	Leonard Explor. Company, Ecuador
1922	The Pure Oil Company, Chicago

Military Service

1917–19	Enlisted man, officer, Corps of Engineers, U. S. Army, France and Germany

Publications.—Geological exploration, petroleum geology; mineral resources

Professional Affiliation (National)
American Geographical Society
American Assoc. Advancement of Science
American Geophysical Union
Geological Society of America
Society of Economic Geologists
American Inst. Mining Met. Engineers
Western Society of Engineers
Tau Beta Pi

A.A.P.G. Activity

1931–	Associate Editor
1931–33	District representative, Great Lakes
1938	Committee for Publication
1940–42	Research Committee
1941	Assistant editor, *Stratigraphic Type Oil Fields*
1946–47	Education Committee

NOMINEES FOR VICE-PRESIDENT, 1950–1951

JOHN EMERY ADAMS

Geologist, Standard Oil Co. of Texas, Midland, Tex.

Born, June 5, 1899, Solon, Iowa

Academic Training
- 1918–23 Univ. of Iowa, Geol., B.A., M.S.
- 1923–24 Univ. of Chicago
- 1925 Univ. of Wisconsin
- 1926–27 Univ. of Texas

Experience
- 1923 Roxana Petroleum Corp.
- 1925–26 Texas A. & M. College
- 1926–27 Texas Bureau Econ. Geol.
- 1927– California Co. and Standard of Texas

Publications.—Petroleum geology and sedimentation

Professional Affiliations (National)
- Amer. Geophysical Union
- Soc. Econ. Paleontologists and Mineralogists
- Geological Society of America (Councilor 45–47)

A.A.P.G. Activity
- 1939–42 Geol. Names and Correlations Com. Permian Sub-Com. 1939
- 1944 Distinguished Lecturer
- 1945–48 Research Committee Consultant

E. W. KRAMPERT

Consulting geologist, Casper, Wyo.

Born, January 21, 1892, Omaha, Neb.

Academic Training
- 1911–15 Carnegie Inst. Technology, B.S.

Experience
- 1917–19 Roxana Petroleum Company
- 1919–32 Prairie Oil and Gas Co. of Wyoming
- 1932–36 Consulting geologist, Casper, Wyo.
- 1936–37 Superior Oil Company
- 1937–49 Consulting geologist, Casper

Publications.—Petroleum geology

Professional Affiliations (National)
- Geological Society of America

Professional Affiliation (National)
- Amer. Assoc. Advancement of Science
- Amer. Geophys. Union
- Amer. Inst. Min. Met. Engineers
- Geological Society of America
- Sigma Xi
- Research and Co-ord. Com., Interstate Oil Compact Comm.

NOMINEE FOR EDITOR, 1950–1951

ALFRED H. BELL

Geologist and head, Oil and Gas Div., Illinois State Geol. Survey, Urbana

Born, June 28, 1895, Simcoe, Ontario

Academic Training
- 1912–15 Univ. Toronto
- 1917 Chem. and Min., B.A.
- 1920–21 Univ. Toronto
- 1921–24 Univ. Chicago
- 1926 Geol., Ph.D.

Experience
- 1914; 1920–23 Canada Geol. Survey
- 1924–26 The Texas Company
- 1926– Illinois State Geol. Survey.

Military Service.—Canadian Overseas Expeditionary Force, 1916–19

Publications.—General geology and petroleum geology

A.A.P.G. Activity
- 1940 Chm., Program Com. Ann. Meeting
- 1940–41, 50 Business Committee
- 1942–44 Committee for Publication
- 1943–46 Research Committee
- 1945–50 Com. Statistics Explor. Drilling
- 1947–50 Medal Award Committee
- 1949– Editor

NOMINEES FOR SECRETARY-TREASURER, 1950–1951

W. J. HILSEWECK

Vice-president and chief geologist, Republic Natural Gas Co., Dallas, Tex.

Born, October 18, 1913, Atoka, Okla.

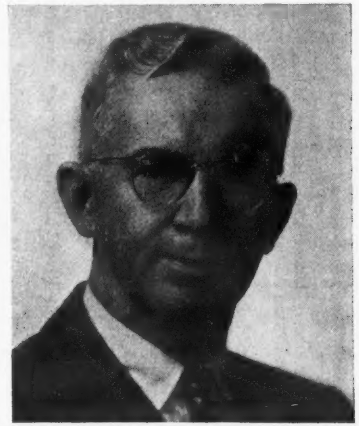
Academic Training
- 1932–35 Univ. Oklahoma
- 1936–38 Univ. Oklahoma (B.S. with honors)

Experience
- 1937–38 Magnolia Petroleum Co., Oklahoma City
- 1938–47 Gulf Oil Corp., Ft. Worth, Midland, Tex.
- 1947– Republic Natural Gas Co., Dallas

Publications.—Field of petroleum geology

Professional Affiliation (National)
Amer. Inst. Min. Met. Engineers

A.A.P.G. Activity
- 1943–49 Distinguished Lecture Committee
- 1944–49 Geologic Names and Correlations Committee
- 1945–47 Com. Statistics Exploratory Drilling



EDWARD F. SHEA

Senior geologist, Stanolind Oil and Gas Co., Tulsa

Born, June 23, 1894, Mahaska, Kansas

Academic Training
- 1916–20 Univ. Nebraska, petroleum geology

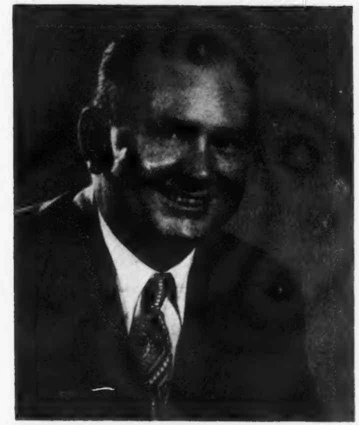
Experience
- 1920–22 Amerada Petroleum Corporation
- 1922–23 Bradstreet Oil Company
- 1923 Assoc., S. J. Caudill, valuation, taxes
- 1924–31 Dixie Oil Company
- 1931– Stanolind Oil and Gas Company

Military Service
- 1918–19 2d Lieut., Field Artillery

Publications.—Petroleum geology and development

Professional Affiliation (National)
American Geophysical Union

A.A.P.G. Activity
- 1936–37 Business Committee
- 1948 Ballot Committee



HENRY N. TOLER

Manager, Geol. and Land Dept., Southern Natural Gas Co., Jackson, Miss.

Born, Oct. 24, 1902, French Camp, Miss.

Academic Training
- 1921–24 Louisiana State Univ.; Geol. B.S., 1925
- 1926–29 Univ. Illinois; Geol. M.S., 1929

Experience
- 1926 Illinois Geological Survey
- 1927–28 The Texas Co., Colombia, S. A.
- 1929–31 Gulf Refining Company
- 1931–36 Consultant and Asst. Miss. State Oi and Gas Supervisor
- 1936–38 Miss. State Oil and Gas Supervisor
- 1938– Southern Natural Gas Company

Publications.—Field of petroleum geology

A.A.P.G. Activity
- 1942–43 Committee for Publication
- 1945 National Service Committee
- 1946–49 Business Committee
- 1946–49 Associate Editor
- 1949 Secretary-Treasurer

FIELD-TRIP GUIDE BOOKS

In response to requests for a list of available guide books published and for sale by A.A.P.G. affiliated societies the following has been compiled from information given by local society officers. Though available at the time of preparing this list, some of these books are becoming scarce. Inquiries should be sent to the addresses indicated.

A.A.P.G. ANNUAL MEETING, St. Louis, Missouri.
Field Conference in cooperation with State Geological Survey of Illinois, Illinois Geological Society, and Missouri Geological Survey and Water Resources, March 18–19, 1949. 30 pp., 8 figs., sections, route map. 8½ by 11. $1.25. Write A.A.P.G., Box 979, Tulsa 1, Oklahoma.

HOUSTON GEOLOGICAL SOCIETY.
Field Trips of A.A.P.G. annual meeting, March 31–April 5, 1941. Hockley Dome, Galveston Bay Drilling, Hastings, Hoskins Mound, Damon Mound, etc. 28 pp., maps, sections, folded road-log map. 8½×11. To A.A.P.G. members, $0.50; non-members, $1.00. Write A.A.P.G., Box 979, Tulsa 1, Oklahoma.

KANSAS GEOLOGICAL SOCIETY, 412 Union National Bank Building, Wichita, Kansas.
1. 10th Field Conference, Pennsylvanian and Permian Rocks of Northeastern Kansas and Northwestern Missouri, 1936. $4.00.
2. 14th Annual Field Conference, Western South Dakota and Eastern Wyoming, 1940. 162 pp., sections, photographs, maps. $5.00.
3. 15th Annual Field Conference, Central and Northeastern Missouri and Adjoining Area in Illinois, 1941. 122 pp., sections, photographs, maps. $5.00.
4. Field Conference, Lower Kansas River Valley, between Kansas City and Lawrence, 1949. $2.00.

MISSISSIPPI GEOLOGICAL SOCIETY, F. T. Holden, secretary, Drawer 1490, Jackson, Mississippi.
1. 5th Field Trip, Upper Cretaceous of West-Central Alabama, December 7–8, 1945. 31 pp., 11 illus. 9×11. Plastic ring binding. $3.65.
2. 6th Field Trip, Upper Eocene, Oligocene, and Lower Miocene of Central Mississippi, June 18–20, 1948. 77 pp., 27 illus. 8½×11. Tape binding. $5.15.
3. 7th Field Trip, Pre-Cambrian and Paleozoic of Northern Alabama and South-Central Tennessee, August 24–27, 1949. 90 pp., 30 illus. 8½×11. Saddle-stitch binding. $4.25.

NORTH TEXAS GEOLOGICAL SOCIETY, Walter L. Ammon, secretary-treasurer, Box 1680, Wichita Falls, Texas.
1. Wichita group of the Permian, Redbed Phase, December 7, 1946; Non-Redbed Phase, December 14, 1946. 4 pp. of road log and mimeographed sketch map, unbound. $1.00.
2. Cambrian and Ordovician Rocks of the Wichita Mountains, May 24, 1947. 10 pp., incl. 2 stratigraphic sections. $1.00.
3. Strawn and Canyon Series of the Brazos and Trinity River Valleys, May, 1940. 10 pp. of road log. $1.00.

PACIFIC SECTION, A.A.P.G., Harold E. Rader, secretary-treasurer, Box 2437, Terminal Annex Station, Los Angeles 54, California.
Field Trip, California Oil Fields, in connection with A.A.P.G. annual meeting, March 24–27, 1947. 132 pp., 41 illus. 8½×11. Spiral ring binder. $2.65.

OKLAHOMA CITY GEOLOGICAL SOCIETY, Joseph M. Sears, treasurer, 2514 First National Building, Oklahoma City, Oklahoma.
Field Trip, November 14–15, 1946. Lower Permian and Upper Pennsylvanian, North-Central Oklahoma. 17 pp., 14 pls. 8½×11. $1.00.

PANHANDLE GEOLOGICAL SOCIETY, Robert B. Totten, secretary-treasurer, Box 46, Amarillo, Texas.
1. Field Conference, Dry Cimarron River Valley, Panhandle of Oklahoma, and Adjoining Area. Front Range of Rocky Mountains in Southeastern Colorado, May 16–18, 1946. 18 pp., 4 maps and sections. 9¼×11½. $1.00.
2. Summer Field Trip, Fossil and Early Man Sites in Texas Panhandle, June 25–26, 1949. 12 pp., 2 sections. 9¼×11½. $1.00.

PITTSBURGH GEOLOGICAL SOCIETY, George C. Grow, Jr., editor, 545 William Penn Place, Pittsburgh, Pennsylvania.
Geology of Northern Part of Appalachian Basin, in connection with A.A.P.G. regional meeting, October 4–9, 1948. 121 pp., maps, charts, sections, 8½×11. Spiral ring binder. $5.00.

ROCKY MOUNTAIN ASSOCIATION OF GEOLOGISTS, Kenneth L. Gow, secretary-treasurer, Superior Oil Company of California, 506 First National Bank Building, Denver, Colorado.
Field Conference in Central Colorado. June 16–19, 1947. 50 pp., 16 figs. 8½×11. $5.00.

SHAWNEE GEOLOGICAL SOCIETY, Marcelle Mousley, secretary-treasurer, Box 169, Shawnee, Oklahoma.
1. Field Conference, Surface Rocks from McAlester Shale to Thurman Sandstone through T.

4-6 N., R. 12-17 E., Pittsburgh County, Oklahoma, June 18, 1938. 12 pp., 2 illus., structure map. 9½×12. $1.00.

2. Field Conference in cooperation with Oklahoma Geological Survey, Surface Rocks from Calvin Sandstone to Permian through T. 6-10 N., Hughes, Seminole, and Pottawatomie Counties, Oklahoma, April 2, 1938. 13 pp., 1 illus. 9½×12. $1.00.

SHREVEPORT GEOLOGICAL SOCIETY, Charles A. Hickcox, secretary-treasurer, Department of Geology, Centenary College, Box 750, Shreveport, Louisiana.

17th Annual Field Trip, September 2, 3, 4, 1949. Cretaceous of Austin, Texas, area. $5.00.

16th Annual Field Trip, May 22, 23, 1948. Ouachita Mountains, Cambrian through Pennsylvanian, and Magnet Cove, Arkansas. $5.00.

15th Annual Field Trip, February 1-2, 1947 Upper and Lower Cretaceous of Southwestern Arkansas. $5.00.

SOUTHEASTERN GEOLOGICAL SOCIETY, Albert C. Raasch, Jr., secretary-treasurer, Box 841, Tallahassee, Florida.

2d Field Trip, November 15-16, 1944. Southwestern Georgia. Papers on Pre-Cambrian-Pleistocene. 63 pp., with maps, 8½×11. $4.50.

3d Field Trip, November 9-10, 1945. Western Florida. Papers on Pre-Paleozoic-Pleistocene. 93 pp., maps, and columnar section. 8½×11. $3.00.

4th Field Trip, September 27-29, 1945. Southeastern Alabama. Tertiary Formation of Alabama. 91 pp., maps, and correlation chart. 8½×11. $3.00.

5th Field Trip, December 5-6, 1947. West-Central Florida. Papers on Paleozoic-Pleistocene. 71 pp., map of area. 8½×11. $3.00.

6th Field Trip, November 18-19, 1949. East-Central Alabama Cretaceous. 75 pp., maps. 8½×11. $3.00.

TULSA GEOLOGICAL SOCIETY, Mary Whitehead, secretary-treasurer, Box 591, Tulsa, Oklahoma.

Field Conference, Western Part of Ouachita Mountains, May, 1947. 56 pp., maps, etc. 9×12. $5.00.

WEST TEXAS GEOLOGICAL SOCIETY, W. A. Waldschmidt, chairman of sale of publication, Box 1814, Midland, Texas.

1. Stratigraphy of Hueco and Franklin Mountains, May 31-June 1, 1946. 11 pp., 3 charts, 1 folded map. 8½×11. $1.50.
2. Guadalupe Mountains of New Mexico and Texas, May 30-31, 1947. 28 pp., 7 charts, illus., 2 folded maps. 8½×11. $2.50.

WYOMING GEOLOGICAL ASSOCIATION, George L. Goodin, treasurer, Box 545, Casper, Wyoming.

1. 3d Annual Field Conference, Wind River Basin, August 11-14, 1948. 198 pp., 38 pp. of maps and illus. $4.25.
2. 4th Annual Field Conference, Powder River Basin, August 9-13, 1949. 98 pp., 35 pp. of illus. 8½×11. Spiral plastic binder. $5.00.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
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MEMORIAL

ELWIN B. HALL
(1891–1949)

Elwin B. Hall died January 20, 1949, following a brief illness. He was stricken suddenly while duck-hunting in the San Joaquin Valley. He suffered a stroke and during the next few days preceding his death rarely gained consciousness.

Everybody knew Elwin B. Hall as "E.B." or "Ebie." His life was one of intense ac-

tivity, inspired by the will to do and by a loving wife who loyally supported him in all of his endeavors.

E.B. was born at Ventura, California, March 24, 1891. He received his A.B. degree at Stanford University in 1914 where he held membership in Sigma Xi and Beta Theta Pi. While there he was an active football player. It is believed that this factor may have laid the foundation for a weakened heart, because he was troubled 8 or 10 years ago by a mild heart attack.

Shortly after E.B. graduated from Stanford he leased from his father 40 acres of walnut land located near Ventura. He married Mary Bacon on January 8, 1916. Together they constructed their first home in the walnut grove which E.B. farmed and operated. Mrs. Hall held the boards and wielded a saw and hammer. Between the two of them, they probably spent some of the happiest days of their life in this simple home in the walnut grove.

E.B., however, was not content to remain exclusively in the walnut business. It was his ambition to have an oil company of his own, so he went about this in a most consistent way, first seeking employment in order to gain experience. He was employed by the Amalgamated Oil Company through his good friend, L. C. Decius, now vice-president and director of exploration, western division, of the Tide Water Associated Oil Company, which company through mergers acquired the properties of the Amalgamated Oil Company in Southern California. This employment began, July 10, 1919, and continued until December 8, 1920. During that time E.B. concentrated his geological work along the Santa Clara River in Ventura and Los Angeles counties. He was probably the first geologist to map and recommend the development of what is now the Del Valle field and the Newhall-Potrero field, both fields being near the Ventura-Los Angeles county line. E.B. called the Del Valle field the Major Anticline and the Newhall-Potrero field was called the Minor Anticline.

Early in the spring of 1920 the Cat Creek field was found in Montana. E.B. felt that an opportunity existed in this direction and so, with the assistance of his father, he went to Montana and acquired certain lands, organizing the Montacal Oil Company. Then he branched out into Wyoming and acquired lands in Baxter Basin which later proved to be productive of gas.

With V. P. Baker, he organized the Hall-Baker Company to operate in California. This company represented a very happy combination, as E.B. did the geological work and Virgil Baker leased the land. They kept afloat in the twenties and early thirties, selling leases and acquiring experience.

E.B. recognized the fact that, as "poor boys," they had to concentrate their efforts in shallow areas, and that he must develop a portable outfit that could drill shallow holes to locate structure. The same resourcefulness that built his first home was used to develop a portable outfit for drilling test wells, so that as the years passed, E.B. became an operator and prospector.

This second line of activity stood him in good stead, for in December, 1936, the Hall-Baker Company secured a contract with the Union Pacific Railroad Company for the drilling of an offset to the General Petroleum Corporation's discovery well at Wilmington, California. After the dissolution of the Hall-Baker Company, E. B. Hall and Company, incorporated in October, 1941, continued in its place, so that the work of E. B. Hall, commenced at Wilmington by the drilling of a single well in 1937 for the Union Pacific Railroad, was never interrupted until his death in 1949. He commenced with 10 employees and one well. There are now 450 employees and more than 550 wells have been drilled, producing about 1,000,000 barrels of oil a month. More than 120,000,000 barrels of oil were produced under the supervision of E. B. Hall, all from land of the Union Pacific Railroad Company. The work which he did to develop the Wilmington field in the face of extremely difficult conditions both on the surface and subsurface is recognized as one of the outstanding pieces of oil development in California.

E.B.'s ingenuity stood him in good stead, for when difficult problems presented themselves he sought a solution. The soft formations of California slough off in an open hole, so that a test of water shut-off is difficult to secure, and tests of productivity of possible oil-bearing sands have required setting a steel liner which would have to be recovered before further work in the well could be done. To meet this problem E.B. first experimented in 1935 with rubber tubing or pipe and then with various other materials until aluminum was finally chosen as a more suitable, drillable material for liners that would keep the hole open but that could be drilled out very quickly. Patent for the aluminum liner was issued to Elwin B. Hall and Arthur L. Armentrout on June 9, 1936. This led to the development of an aluminum stinger which was used on cementing jobs, so as to put a batch of cement 20 feet below the shoe of the water string. Part of this idea was developed by Howard K. Pieper, who also was an employee of the Amalgamated and Associated oil companies.

Later on when the formations became mudded and it was difficult to secure production, E.B. tackled the problem of securing a chemical that would remove the mud cake. This chemical was later patented and is now commercially exploited by a service company.

As previously noted, E.B.'s ambition was to own his own oil company. This, too, was accomplished. After drilling or causing many wildcats to be drilled and through a long period of years, he was able to develop production on a lease of his wholly owned Drilling and Production Company on the Tejon Ranch in Kern County. The first oil was produced at 4,500 feet in the Reserve Zone in 1944. Later, however, shallower production has been developed at approximately 2,600 feet. On this property there are now 15 wells, producing 650 barrels per day, but a good part of the land still remains to be drilled.

E. B. Hall had time also for work in oil conservation. He served as a member of the Conservation Committee of California Oil Producers, and was active on the Allocation Committee, wherein he did not hesitate to tackle difficult problems where an arbitrator was needed.

This continuing drive throughout his life eventually took its toll, and a cheerful, kindly friend and diligent worker was lost to the oil industry.

E.B. is survived by his wife, Mary Bacon Hall, his daughter, Mrs. Richard C. Bergen, and her two children, and by his son, E. B. Hall, Jr., and his twin sons. Incidentally, the son, E. B., Jr., promises to follow in his father's footsteps in the management of the E. B. Hall Company.

E. B. Hall was a member of the American Association of Petroleum Geologists, the American Institute of Mining and Metallurgical Engineers, and the American Petroleum Institute. He possessed a wonderful driving force and withal a generous and kindly disposition. He never spoke ill of anyone and always had time to help those who appealed to him. Those of us who knew him and respected him will miss him; the world is better because of his having lived in it.

JOSEPH JENSEN

Los Angeles, California
September, 1949

BURTON ARMAND LILIENBORG

(1900–1949)

The profession has lost a man who loved geology and the work of a geologist. His early passing is very much regretted by his many friends.

Burton A. (Doc) Lilienborg was born, April 15, 1900, at Axtell, Kearney County, Nebraska, the son of Bathilda Hakanson Lilienborg and Andrew Lilienborg, both being natives of Sweden who came to this country in 1890.

He attended elementary school in Axtell and Hastings, Nebraska. In 1911, his parents moved to Hildreth, Nebraska, at which place he completed his grade and high school education. His first two years in college were spent at Doane College in Crete, Nebraska, where he specialized in music. With the introduction of sound pictures, using what is commonly termed "canned music," he saw no future in a musical career, and in the meantime, having become interested in geology, enrolled at the University of Nebraska, from

BURTON ARMAND LILIENBORG

which school he received his A.B. degree in January, 1926. He was a member of Sigma Gamma Epsilon (Delta Chapter), geology, mining, and metallurgy fraternity, the Tulsa Geological Society, and the American Association of Petroleum Geologists.

Upon completion of his work at the University of Nebraska, he joined the M.T.C. Oil Company, Coffeyville, Kansas, as geologist and private secretary to the president of the company. Later in the year this company was moved to Tulsa, Oklahoma. He continued with the M.T.C. Company until June, 1929, when he joined Kent K. Kimball as a consulting geologist.

During the year 1930, he joined the geological staff of the Independent Oil and Gas Company under the direction of A. I. Levorsen. While with the Independent the details of his work dealt mainly with Kansas. Late in 1930, when the Independent sold its interests to the Phillips Petroleum Company, he transferred to Bartlesville, aiding with the consolidation of records of the two companies. For a short period he worked for the United States Geological Survey in Bartlesville, but returned to Tulsa, where he maintained a home. He was again associated with Kent K. Kimball as a consultant, later opening an office of his own as consultant and appraisal engineer. He continued in this capacity until January, 1937, at which time he joined Forrest H. Lindsay and associates of the Southwestern Royalty Company, and later the National Associated Petroleum Company, as geologist, in which capacity he remained until his death, July 26, 1949.

He had lost his health for several years, beginning some time in 1942 while he was stationed in Evansville, Indiana, supervising the activities of the National Associated Petroleum Company production in Illinois. He continued with work regularly until October, 1947, when he was stricken with an illness which was the forerunner of his final illness. During the intervening time he had spent very little time at his desk.

He was married, February 15, 1930, to Miss Eloise Carter of Tulsa, Oklahoma, who survives him. He is also survived by his father, Andrew Lilienborg, of Kensington, Kansas, and a brother, Maynard, of California.

Apart from being an able geologist, he was also an accomplished musician and sang for a number of years with "The Tulsans."

KENT K. KIMBALL

Tulsa, Oklahoma
September 23, 1949

DWIGHT HUGH FORTINE

(1904–1949)

Dwight Hugh Fortine passed away in Glendale, California, on August 3, 1949, surviving his wife, Alice, by only 2 days, both having been ill for some time. These inseparable companions of many years were laid to rest together in Forest Lawn Memorial Park.

They are survived by two sons, Eugene, age 19, who is majoring in petroleum engineering at Stanford University, and Frederick, age 14, who now resides with his grandmother in North Hollywood.

Dwight is also survived by his mother, Mrs. Lina Fortine, and two brothers, Wayne and Douglas.

Dwight was born on November 19, 1904, on the Orcutt oil field lease near Santa Maria, California, the son of Fred and Lina Fortine. He attended elementary schools in the shadow of the California oil fields, completing his high school education at Taft, California. In 1922 he entered Stanford University and graduated in 1926 with an A.B. degree in geology.

Dwight was first employed by the Barnsdall Oil Company during his summer vacations in 1924 and 1925, working as a roughneck in the drilling department at the Rosecrans field.

For a period of 2 years after graduating from college he gained practical experience working on drilling rigs, working for the California State Mining Bureau as an inspector, and engaging in petroleum engineering for the Miley Oil Company at Goleta, California. In May, 1928, he was employed as a petroleum engineer by the Shell Oil Company, Inc., and shortly thereafter was transferred to Maracaibo, Venezuela, for the Caribbean Petroleum Company for a period of 4 years.

He became a member of the A.A.P.G. in 1930.

In 1931 Dwight returned to California where he was employed as a petroleum engineer by the Barnsdall Oil Company. In that capacity he was actively engaged in the expansion of the Rosecrans, Elwood, and Mt. View oil fields until 1935, when he was made production foreman.

In 1943 he became drilling engineer, and devoted the greater part of his time to the

DWIGHT HUGH FORTINE

development of the Newhall-Potrero field. He was appointed to the position of chief geologist for the Pacific Coast division of the Barnsdall Oil Company in March, 1948, and held that position until the time of his death. Dwight's ability and judgment are evidenced by his steady advancement within his company. He had an enormous capacity for work, and working hours or holidays meant little to him when there was a job to be done.

Dwight's many friends from the field department to the management of his company will remember him for his unswerving loyalty to his job, and his impartial friendship and cooperation with those he supervised as well as to those who supervised him. A number of them will also remember hunting and fishing trips with him which he enjoyed so much. He was a good father and pal to his sons. His many friends outside of the Barnsdall Oil Company will remember him for his quiet, friendly nature and demonstrated ability as an engineer and geologist.

All of his friends will remember him for the indomitable courage and faith displayed by him in his final and unsuccessful fight to regain his health. The loss of this devoted couple is keenly felt.

R. T. WHITE

Los Angeles, California
September, 1949

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
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AT HOME AND ABROAD

NEWS OF THE PROFESSION

ILLINOIS GEOLOGICAL SURVEY

Appropriations for the biennium 1949–1951 to the Illinois Geological Survey were recently made by the State Legislature in the amount of $1,478,530, according to MORRIS M. LEIGHTON, chief of the Survey. This is an increase of $331,940 over the preceding biennium which ended, June 30, 1949.

The same Act authorized a new classification of salaries for positions on the scientific staff as recommended by the State Board of Natural Resources and Conservation. This made possible a higher level of salaries.

The State Geological Survey and the State Natural History Survey occupy jointly their own building, the Natural Resources Building, on the campus of the University of Illinois, which was built and equipped in 1940 at a cost of approximately $800,000. The Geological Survey also has a separate Applied Research Laboratory for large-scale work, situated near the University Power Plant, which was also built in 1940 at a cost of approximately $150,000.

Two wings are now being added to the Natural Resources Building, an east wing for the Geological Survey and a west wing for the Natural History Survey, which will virtually double the space for both organizations, at a cost of $1,765,000. These funds were made available by the Legislature 2 years ago. An additional sum of $660,000 was appropriated by the Legislature during its session just ended for fixed equipment, furniture, and scientific apparatus for both wings, and a supplementary appropriation was made, amounting to $86,000 for alterations in the present building to accommodate certain laboratory and office changes incident to expansion.

These new facilities will permit continuing on a somewhat expanded scale the program of integrated research by geologists, chemists, physicists, engineers, and mineral economists which was begun in 1931.

The growth of the Illinois Geological Survey has been steady and responsive to the results arising out of its research and to new opportunities for service in its field. At the present time the staff comprises 120 persons regularly employed on a full-time basis. Of this number there are 36 geologists, 12 chemists, 2 physicists, 3 engineers, 3 mineral economists, 9 supervisory assistants, and 33 research and technical assistants.

EUGENE HOLMAN, president of Standard Oil Company (New Jersey), has accepted the chairmanship of the New York convention committee of the Thirty-Sixth National Foreign Trade Convention to be held October 31–November 2 at the Waldorf-Astoria, New York.

CHARLES R. KOLB is with the Snare Engineering Corporation, Santiago, Chile.

The Houston Geological Society luncheon program on September 26 was a paper on "Aluminum—from Mine to Metal," by H. S. MCQUEEN, of the Aluminum Company of America.

HUNTER C. GOHEEN has left the Texas Petroleum Company at Bogota, Colombia, to join the Antilles Petroleum Company, Ltd., at Trinidad, B. W. I.

JOHN E. COPPINGER is employed as a petroleum engineer trainee in the cement department of the Halliburton Oil Well Cementing Company, Snyder, Texas.

GLENN M. FEDDEKSON is employed by the Shell Oil Company, Inc., at Pueblo, Colorado.

J. HOOVER MACKIN, professor of geology at the University of Washington, and with the United States Geological Survey during the past 5 summers, spoke on "Altitudes and Local Relief of the Big Horn Area during the Cenozoic," before the Rocky Mountain Association of Geologists at Denver, Colorado, November 2. This was an A.A.P.G. Distinguished Lecture.

HERBERT D. HADLEY, formerly with Stewart and Hadley, has opened an office as consulting geologist at 801 Grand Avenue, Billings, Montana.

ROBERT A. BISHOP is now engaged as a consulting geologist with offices at 812 Lancaster Building, Calgary, Alberta, Canada. He was former manager of exploration with the Socony-Vacuum Exploration Company.

GLEN C. THRASHER, who has been associated with HUGH A. STEWART in the oil and gas consulting business in Denver, Colorado, will carry on the business, maintaining his office in the Continental Oil Building, Denver, Colorado. Stewart, who was recently appointed director of the Oil and Gas Division, United States Department of the Interior, is retiring from the firm.

T. A. LINK will be the featured speaker at the annual dinner meeting of the Kansas Geological Society, Tuesday, December 6. During the meeting "The Geo-Follies of 1950" will also be presented and officers for the coming year will be elected.

A.A.P.G. PACIFIC SECTION PAPERS, NOVEMBER 17–18, 1949

Geology of West Flank of Temblor Range, Otto Hackel and Roy Turner.
San Ardo Oil Fields and Vicinity, Thomas A. Baldwin.
Cuyama Valley Geology and Development, Rollin Eckis.
Geology North of Brooks Range, Alaska, O. F. Kotick.
Luncheon speaker, President C. W. Tomlinson.
Geological Interpretation of Offshore Seismic Results, Curtis H. Johnson and Robert B. Galeski.
Configuration of Basement Complex in Los Angeles Basin, Jack E. Schoellhamer.
Legal Aspect of Tideland Controversy, William F. Clary.
Theory of Transgressive and Regressive Bioherm Development, Theodore A. Link.
Geology and Exploration of Western Canada, Theodore A. Link.
Geology of Placerita Oil Field, Robin Willis.
Geology of North Sulphur Mountain, Irving T. Schwade and Spencer Fine.
Vaqueros Sandstone of Santa Barbara Coast, E. Robt. Orwig.
Exploration of Santa Rosa Island, Robert E. Anderson and Lowell E. Redwine.
Investigations of Ocean Floor, Warren C. Thompson.
Guijarral Hills Developments, John S. Loofbourow.
Cenozoic Correlations, Robert T. White.
Exploration and Development, Graham B. Moody.
Time of Oil Accumulation, A. L. Levorsen.
Stratigraphy of Eastern Nevada, Chas. W. Merriam.
Some Observations on the Structure of Eastern Nevada, Fred L. Humphrey.

R. O. Young, recently with the Creole Petroleum Corporation in Venezuela, is with the Trinidad Leaseholds, Ltd., at Pointe-à-Pierre, Trinidad, B. W. I.

Charles S. Percy is connected with the Seeligson Engineering Committee, San Antonio, Texas. He was formerly geologist with the Stanolind Oil and Gas Company.

James W. Clark, formerly with the Amerada Petroleum Corporation, is now associated with the Kansas-Nebraska Natural Gas Company, Great Bend, Kansas.

Stephen S. Winters, formerly at Newark Colleges, Newark, New Jersey, has joined the faculty of the Florida State University, at Tallahassee, as assistant professor in geology.

Joe A. Laird, consulting geologist of Houston, has become a member of the faculty of the department of petroleum engineering at the Texas A. and M. College, College Station, Texas.

Joseph Lintz, Jr., recently with the General Petroleum Corporation at Durango, Colorado, is taking additional courses at the Johns Hopkins University, Baltimore, Maryland.

Paul L. Lyons, of the Carter Oil Company, Tulsa, has been appointed technical assistant to H. F. Moses, vice-president in charge of exploration and research.

B. G. Martin, of the Gulf Oil Corporation, Houston, has been appointed assistant to J. H. Russell, vice-president in charge of production.

J. M. Hansell is chief geologist for the Canadian division of the Sun Oil Company, with headquarters at 525 Seventh Avenue West, Calgary, Alberta. Hansell has been regional geologist in the Dallas, Texas, office.

The Fort Worth Geological Society met at dinner at the Hotel Texas, September 19, to hear president C. W. Tomlinson speak on "Pennsylvanian Paleogeography of Southern Oklahoma." Guests at the dinner were the past-presidents of the Association who are also members of the Fort Worth Society. They were H. B. Fuqua, F. L. Aurin, and Henry A. Ley, and M. G. Cheney of Coleman, Texas. J. Earle Brown, former business associate, paid tribute to the late J. Elmer Thomas, first president of the Association, who died last month. Since F. H. Schouten, president of the Fort Worth Society, has been transferred by the Stanolind to Canada, H. C. Vanderpool has been made president and W. Baxter Boyd has been appointed vice-president. Thomas Nichols remains secretary-treasurer.

French R. White, Jr., has left the Magnolia Petroleum Company to join the Puenticitas Oil Company, Corpus Christi, Texas.

C. E. Thiebaud has left Venezuela where he was employed by the Caribbean Petroleum Company. He is stationed at The Hague, Holland, with the Bataafsche Petroleum Mij.

Harold J. Kleen is central division manager in charge of geological, land, and scouting activities of the Kerr-McGee Oil Industries, Inc., Oklahoma City. Kleen was formerly district geologist for the Skelly Oil Company at Oklahoma City.

John W. Gabelman, instructor in geology at the Colorado School of Mines, is now geologist in the mining department of the Colorado Fuel and Iron Corporation, Pueblo, Colorado.

WAYNE LOEL, consulting geologist and engineer, maintains his headquarters at 804 Subway Terminal Building, Los Angeles, California.

JOHN O. GALLOWAY, formerly vice-president of the California Standard Company, recently opened a consulting office at Calgary, Alberta. He is connected with the Canadian Bank of Commerce as petroleum consultant.

The first technical meeting of the Tulsa Geological Society, for the fall season was held in the auditorium of Lorton Hall at the University of Tulsa, 8:00 P.M., Monday, October 3. The subject of the evening was "Pennsylvanian Paleogeography of Southern Oklahoma," by C. W. TOMLINSON, president of A.A.P.G.

WALLACE L. WILGUS, production geologist with the Shell Oil Company, was recently transferred from New Orleans, Louisiana, to Tulsa, Oklahoma where he will assume the duties of area production geologist for Shell's Tulsa area.

President C. W. TOMLINSON presented his paper, "Lost Reserves," to the Panhandle Geological Society, Amarillo, Texas, September 21. The Auxiliary Society entertained Mrs. Tomlinson with a review of "Tales of the South Pacific" given by Mrs. Howard Lynch of Amarillo. The Tomlinsons were guests of both societies at this dinner meeting.

MAX L. KRUEGER, Rocky Mountain division manager for Union Oil Company, resigned, November 15, to become vice-president in charge of exploration for the Conorada Petroleum Corporation with headquarters in New York City. E. R. ATWILL, formerly assistant chief geologist of the Pacific Coast division for the Union Oil at Los Angeles, becomes a division manager for the company's Rocky Mountain operations.

NATIONAL RESEARCH FELLOWSHIPS

The National Research Council announces that its National Research Fellowships in the Natural Sciences will be continued in 1950. It is the purpose of these fellowships to promote fundamental research in the natural sciences. These fellowships are awarded to citizens of the United States or Canada, and they are generally restricted to persons under 35 years of age. All requirements for the doctorate must have been completed prior to assuming the fellowship, and the Fellow must have demonstrated a high order of ability in research. Fellowships will be awarded by the Natural Sciences Fellowship Board of the N. R. C. at a meeting to be held early in 1950. Applications to be considered at this meeting must be filed on or before January 1, 1950. Tenure of the fellowship may begin at any appropriate time after the board meeting. These fellowships are available in the fields of mathematics, astronomy, physics, chemistry, geology, geophysics, paleontology, physical geography, botany, zoology, biochemistry, biophysics, agriculture, forestry, anthropology, and psychology. Further information and application blanks may be obtained from the Fellowship Office, National Research Council, 2101 Constitution Avenue, N. W., Washington 25, D. C.

RENE POMEYROL after a long stay at home, is now consulting geologist for the Bureau de Recherches de Petrole, 85, Boulevard du Montparnasse, Paris, 6°, France.

M. J. MUNN, age 75 years, died at Texarkana, Texas, October 2. He was engaged in geological work in Oklahoma for many years after 1912. He was a graduate of the University of Arkansas and had served on the United States Geological Survey.

E. B. NOBLE, of the Union Oil Company of California, was appointed, effective October 1, general manager for Canada. His headquarters office is in Calgary, Alberta, and he will be responsible for all exploration and development north of the International line.

STANLEY G. WISSLER has been appointed chief geologist of the Pacific Coast division of the Union Oil Company, with headquarters in Los Angeles, succeeding L. N. WATERFALL, who has resigned to enter consulting practice. R. G. GREENE is manager of exploration in the Pacific Coast division.

LON D. CARTWRIGHT, chief geologist of the Gulf division of the Union Oil Company, has been appointed chief geologist for all Union operations.

PAUL E. M. PURCELL announces the Purcell Exploration Service, Wichita Falls, Texas.

R. E. WILLS, recently with the Magnolia Petroleum Company, is at Lawrence at the University of Kansas, geology department, Lindley Hall.

JOHN W. HUDDLE has moved from the University of North Carolina to 301-B Administration Building, University of Kentucky, Lexington.

JOHN P. LEWIS has left the Sohio Petroleum Company to become geologist for the Chapman Oil Company in Mt. Pleasant, Michigan.

The Pacific Section of the Association held a luncheon meeting, October 6, at the Clark Hotel, Los Angeles, California, and listened to R. R. MARTEL, professor at the California Institute of Technology, Pasadena, present his paper "Studies of Earthquake Resistant Structures."

ARTHUR GILBERTSON HUTCHISON, age 47 years, was killed in an accident, August 6, while examining the Lower Carboniferous rocks on the Cornwall Coast, near the town of Tenby, England. He was connected with the N. V. de Bataafsche Petr. Mij. at The Hague.

N. B. LARSH, formerly with the Sinclair Oil and Gas Company, Midland, Texas, is now with the Danciger Oil and Refining Company.

FRANK O. BENNETT has entered the field of consulting geology, 308 Petroleum Building, Wichita, Kansas. He has been with the firm of Rust, Ward, and Bennett.

J. J. DOZY has left The Hague to go to Indonesia in the employ of the Bataafsche Petroleum Mij. The address is Willemslaan 2, Batavia, Indonesia.

FRITZ GAYLORD NAGEL is on leave from the Ohio Oil Company to do graduate work at the Northwestern University, Evanston, Illinois.

WILLIAM GRAY PARK has moved from Golden, Colorado, to work for the Petroleum Service Company, Alamo National Building, San Antonio, Texas.

CYRIL J. PERISEK is employed in Midland, Texas, by the Residue Research Laboratory.

GEORGE E. CARVER, JR., recently resigned his position with the Kerr-McGee Oil Industries, Inc., to join the United Carbon Company as geologist. He is at Sayre, Oklahoma.

JOHN A. STOKLEY resigned from the University of Kentucky, geology department, in September, to attend the Washington University, St. Louis, Missouri, to do work toward the Ph.D. in geology.

A. J. EARDLEY has resigned from the University of Michigan and has accepted a professorship in the department of geology of the University of Utah, Salt Lake City, Utah.

HORACE G. RICHARDS, associate curator of geology and paleontology at the Academy of Natural Sciences of Philadelphia, returned recently from a month's trip to Europe. On

the trip he conferred with numerous European geologists and also studied Pleistocene and Cretaceous localities in England, France, Czechoslovakia, Poland, Denmark, and the Netherlands. He has been appointed special lecturer in geology at the University of Pennsylvania for the year 1949–1950.

E. RAYMOND RING, JR., senior subsurface geologist at the Barco Concession of Colombia, has left the Socony-Vacuum Oil Company to return to the Rocky Mountain area after having completed 3 years of tropical work.

THEODORE A. LINK, consulting geologist of Toronto and Calgary, Canada, vice-president of the A. A. P. G. and of the Geological Association of Canada, delivered a talk on "Western Canadian Geology" at the Canadian Institute of Mining and Engineering Society meeting at Vancouver on October 18, and a similar talk to the Pacific Section of the A. A. P. G. at the annual fall meeting in Los Angeles, November 17. He also took part in a field trip through the coral-reef area of West Texas and New Mexico in connection with the annual meeting of the Geological Society of America, at El Paso, Texas, November 10–12. During the fall he delivered a series of lectures on "The Theory of Transgressive and Regressive Reefs or Bioherm Development, and the Origin of Oil within Them." This series is sponsored by the Association as one of the Distinguished Lecture tours.

LEONARD W. ORYNSKI announces the opening of his office as consulting geologist at 604 Republic Bank Building, Dallas, Texas.

H. B. FUQUA is chairman of the board of directors of the Texas Pacific Coal and Oil Company, Fort Worth, Texas, and C. E. YAGER is president of the company.

VIRGIL R. D. KIRKHAM died at Spokane, Washington, September 24, at the age of 55 years.

The Southeastern Geological Society has completed its Mesozoic cross sections covering Florida, eastern Alabama, and Georgia, prepared for the Gulf Coast section of the Mesozoic sub-committee, geologic names and correlations committee of the American Association of Petroleum Geologists. Five cross sections on four sheets comprise a set. The cost is $8.00 per set. Sets will not be broken. Orders may be sent to the Southeastern Geological Society, Box 841, Tallahassee, Florida.

The Southern Production Company, Inc., Shreveport, Louisiana, recently announced that C. D. STEPHENSON, chief geologist, has been elected vice-president of the company.

H. M. KIRK is manager of the Tide Water Associated Oil Company, Royal Bank Building, Regina, Saskatchewan, Canada.

ELDON J. PARIZEK is professor of geology at the University of Georgia, Athens, Georgia.

JEAN E. SOADY is doing post-graduate work at Augustana College, Rock Island, Illinois.

RAYMOND J. STIPEK has left the Union Oil Company of California to join the firm of Keans, Springmann, and Stipek, General Petroleum Building, Los Angeles, California.

W. A. HALAMICEK, JR., is a graduate student at the University of Texas, Austin, Texas.

MELVIN N. LEVET is research engineer with the California Research Corporation, La Habra, California.

WILLIAM C. RASMUSSEN has left the Speed Oil Company to take charge of United States Geological Survey studies of ground-water resources on the Eastern Shore of Maryland, in cooperation with the Maryland Department of Geology, Mines, and Water Resources. Headquarters for the work are at Salisbury, Maryland.

The first fall meeting of 1949 of the Eastern Section of the Association was called to order by president HOLLIS D. HEDBERG on September 20, in New York City. There were 46 present at the dinner meeting in the Mining Club: 41 members and 5 visitors. The following officers were elected for the year 1950: DOUGLAS A. GREIG, president, FRANK NOTESTEIN, vice-president, BROOKS ELLIS, treasurer, and A. J. HAWORTH, secretary. MARSHALL KAY spoke on "Geosynclines."

A.A.P.G. REGIONAL MEETING, OKLAHOMA CITY, JANUARY 12–13, 1950

The Association has accepted the invitation of the Oklahoma City Geological Society to hold a mid-year regional meeting at Oklahoma City on January 12 and 13, 1950. Subjects for presentation should be restricted to Mid-Continent geology. Authors may submit titles and abstracts to F. H. KATE, 608 Colcord Building, Oklahoma City 2, Oklahoma. Officers of the Oklahoma City Geological Society are: president, RIZER EVERETT, Carter Oil Company; secretary, L. W. CURTIS, Sohio Petroleum Company; treasurer, JOSEPH M. SEARS, independent. Further notices will be sent the members.

The first regular luncheon meeting of the Oklahoma City Geological Society for the 1949–1950 season was held on September 8. CRAIGN SMITH, Oklahoma County Assessor, spoke on "Advalorem Taxes." At the regular meeting on September 22, the Society heard a talk by H. M. RACKETS on the topic of "Gem Cutting." At a special evening meeting on October 5, the speaker was WARREN BEEBE. His subject was "Geologic Responsibility in Seismic Exploration."

RUFUS M. SMITH arranged the following technical program for the Pacific Section of the Association, at Los Angeles, California, October 17: W. H. COREY, Continental Oil Company, Los Angeles, "South Coast Correlations"; O. E. BOWEN, JR., State Division of Mines, San Francisco, "Stratigraphic and Structural Features of the Barstow Quadrangle and Vicinity"; E. D. LYNTON, California Research Corporation, San Francisco, "A Geologist's Views of the French Oil Industry and Europe."

W. D. OWSLEY, Halliburton Oil Well Cementing Company, spoke on the subject "The Hydrafrac Process," before the Houston Geological Society, Houston, Texas, October 10.

The following technical programs have been presented by the Tulsa Geological Society, Tulsa, Oklahoma: October 14, "Observations on Cuba," CLARK MILLISON, consultant geologist; October 17, "Pennsylvanian Sediments on the Northerly Flank of the Pauls Valley Arch," LON B. TURK, geologist, 1st National Bank, Oklahoma City; October 21, "The Missouri-Virgil Boundary, Kansas-Oklahoma Line to the Arbuckle Mountains, Oklahoma," MALCOLM C. OAKES, Oklahoma Geological Survey.

The Kansas Geological Society has held recent meetings in Wichita with programs as follows: October 25, L. G. CHOMBART, "Factors Involved in Practical Electric-Log Analysis"; November 4, EUGENE C. REED, Nebraska Geological Survey. The fall field trip was held on October 29 under the leadership of J. M. JEWETT, of the Kansas Geological Survey.

PROFESSIONAL DIRECTORY

CALIFORNIA

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Editor - - - - - - - - - - - R. A. Geyer
Humble Oil and Refining Company
Houston, Texas

Secretary-Treasurer - - - - - - - K. E. Burg
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6000 Lemmon Ave., Dallas, Texas

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1348 Esperson Bldg., Houston, Tex.

Business Manager - - - - - - Colin C. Campbell
Room 210, 817 South Boulder, Tulsa, Oklahoma
P.O. Box 1614

CALIFORNIA

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Richfield Oil Corporation
Room 430, Richfield Bldg.
Los Angeles 13, California

Vice-President - - - - - - - John E. Kilkenny
Chanslor-Canfield Midway Oil Company
4549 Produce Plaza West, Los Angeles 11

Secretary-Treasurer - - - - - Harold E. Rader
Standard Oil Company, Box 2437, Terminal Annex
Los Angeles 54

Monthly meetings. Visiting geologists are welcome.

CALIFORNIA

SAN JOAQUIN GEOLOGICAL SOCIETY

BAKERSFIELD, CALIFORNIA

President - - - - - - - Robert B. Hutcheson
The Superior Oil Company, Box 1031

Vice-President - - - - - - Floyd L. Johnson
Honolulu Oil Corporation

Secretary-Treasurer - - - Maxwell G. Caben
Seaboard Oil Company of Delaware, Box 7

Dinner meetings on 2d Tuesday of each month or as announced, El Tejon Hotel, Bakersfield.

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DENVER, COLORADO

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U. S. Reclamation Service

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U. S. Geological Survey
136 New Customhouse

2d Vice-President - - - - - - - E. W. Scudder
J. M. Huber Corporation
Box 2098

Secretary-Treasurer - - - - - Kenneth L. Gow
Superior Oil Company of California
506 First National Bank Building

Evening dinner (6:30) and technical program (8:00) first Tuesday each month or by announcement.

FLORIDA

SOUTHEASTERN GEOLOGICAL SOCIETY

Box 841
TALLAHASSEE, FLORIDA

President - - - - - - - - - W. C. Blackburn
Humble Oil and Refining Company, Box 506

Secretary-Treasurer - - - - - - Albert A. Raasch
Humble Oil and Refining Company,
Box 506

Meetings will be announced. Visiting geologists and friends are welcome.

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ILLINOIS GEOLOGICAL SOCIETY

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C. E. Brehm Drilling & Producing
Mt. Vernon

Vice-President - - - - - - - - - Joseph Neely
Magnolia Petroleum Company
Box 535, Mt. Vernon

Secretary-Treasurer - - - - - Lloyd A. Harris
Carter Oil Company, Box 568, Mattoon

Meetings will be announced.

INDIANA-KENTUCKY

INDIANA-KENTUCKY GEOLOGICAL SOCIETY

EVANSVILLE, INDIANA

President - - - - - - - - H. W. Bodkin
Superior Oil Company

Vice-President - - - - - - - - D. G. Sutton
Sun Oil Company, Box 717

Secretary-Treasurer - - - - - - J. B. Vaughan
Ashland Oil and Refining Company
Henderson, Kentucky

Meetings will be announced.

KANSAS

KANSAS GEOLOGICAL SOCIETY

WICHITA, KANSAS

President - - - - - - - - - Don W. Payne
Sinclair Prairie Oil Company

Vice-President - - - - - - - - T. G. Wright
Stanolind Oil and Gas Company

Secretary-Treasurer - - - - Victor F. Reiserer
Superior Oil Company, 510 K.F.H. Bldg.

Regular Meetings: 7:30 P.M., Geological Room, University of Wichita, first Tuesday of each month. Noon luncheons, first and third Monday of each month at Wolf's Cafeteria. The Society sponsors the Kansas Well Log Bureau, and the Kansas Well Sample Bureau, 508 East Murdock. Visiting geologists and friends welcome.

OKLAHOMA

SHAWNEE GEOLOGICAL SOCIETY
SHAWNEE, OKLAHOMA

President - - - - - - - - Doyle M. Burke
The Texas Company, Box 1007

Vice-President - - - - - - - - Jack W. Davies
Halliburton Oil Well Cementing Company

Secretary-Treasurer - - - - - Marcelle Mousley
Atlantic Refining Company, Box 169

Meets the third Thursday of each month at 8:00 P.M., at the Aldridge Hotel. Visiting geologists welcome.

TULSA GEOLOGICAL SOCIETY
TULSA, OKLAHOMA

President - - - - - - - - - - L. H. Lukert
The Texas Company, Box 2420
1st Vice-President - - - - - Daniel A. Busch
Carter Oil Company, Box 801
2d Vice-President - - - - John M. Nash
Shell Oil Company, Box 1191
Secretary-Treasurer - - - - Mary Whitehead
Stanolind Oil and Gas Company, Box 591
Editor - - - - - - - Oscar E. Wagner, Jr.
Mid-Continent Petroleum Corporation, Box 381
Business Manager, Digest - - - - V. L. Frost
Ohio Oil Company, Thompson Building
Meetings: First and third Mondays, each month, from October to May, inclusive, at 8:00 P.M., University of Tulsa, Lorton Hall. Luncheons: Every Friday (October-May), Chamber of Commerce Building.

PENNSYLVANIA

PITTSBURGH GEOLOGICAL SOCIETY
PITTSBURGH, PENNSYLVANIA

President - - - - - - - Charles F. Bassett
Gulf Oil Corporation, Box 1166
Vice-President - - - - - - - R. E. Sherrill
University of Pittsburgh
Secretary - - - - - - - - - C. E. Prouty
University of Pittsburgh
Treasurer - - - - - - - - - Sidney S. Galpin
Peoples Natural Gas Company
545 William Penn Place

Meetings held each month, except during the summer. All meetings and other activities by special announcement.

TEXAS

ABILENE GEOLOGICAL SOCIETY
ABILENE, TEXAS

President - - - - - - - - - - - J. R. Day
Pan American Production Company

Vice-President - - - - - David M. Grubbs
Drilling and Exploration Company

Secretary-Treasurer - - - - - C. S. Noland
Skelly Oil Company

Meetings: 2d Thursday of each month, 7:30 P.M., Wooten Hotel.

TEXAS

CORPUS CHRISTI GEOLOGICAL SOCIETY
CORPUS CHRISTI, TEXAS

President - - - - - - - - James D. Burke
Seaboard Oil Company of Delaware, Box 601
Vice-President - - - - - W. H. Wallace, Jr.
La Gloria Corporation, Driscoll Building
Secretary-Treasurer - - - - H. W. Volk, Jr.
Tide Water Associated Oil Company
Driscoll Building

Regular luncheons, every Thursday, Terrace Annex Room, Robert Driscoll Hotel, 12:00. Special night meetings by announcement.

DALLAS GEOLOGICAL SOCIETY
DALLAS, TEXAS

President - - - - - - - - - John T. Rouse
Magnolia Petroleum Company
P.O. Box 900
Vice-President - - - - - - - H. V. Tygrett
The Atlantic Refining Company
P.O. Box 2819
Secretary-Treasurer - - - - Gilbert P. Moore
Consulting, 501 Continental Building
Executive Committee - - - - - Edgar Kraus
Atlantic Refining Company
Box 2819

Meetings: Monthly luncheons and night meetings by announcement.

EAST TEXAS GEOLOGICAL SOCIETY
TYLER, TEXAS

President - - - - - - - - - - G. C. Clark
Stanolind Oil and Gas Company
Box 660

Vice-President - - - - - R. M. Trowbridge
Consultant, 225 Owen Building

Secretary-Treasurer - - - - - Rosella L. Bunch
Shell Oil Company, Inc., Box 2037

Luncheons: Each week, Monday noon, Blackstone Hotel.
Evening meetings and programs will be announced. Visiting geologists and friends are welcome.

FORT WORTH GEOLOGICAL SOCIETY
FORT WORTH, TEXAS

President - - - - - - - H. C. Vanderpool
Texas Pacific Coal and Oil Company
Box 2110
Vice-President - - - - - - - W. Baxter Boyd
Continental Oil Company
1710 Fair Building
Secretary-Treasurer - - - - Thomas Nichols
Rowan Oil Company
Commercial Standard Building
Meetings: Luncheon at noon, Hotel Texas, first and third Mondays of each month. Visiting geologists and friends are invited and welcome at all meetings.

TEXAS

HOUSTON GEOLOGICAL SOCIETY
HOUSTON, TEXAS

President - - - - - - - Hershal C. Ferguson
Consultant, 935 Mellie Esperson Building
Vice-President - - - - - - - - - R. R. Rieke
Schlumberger Well Surveying Corporation
Secretary - - - - - - - - - James H. McGuirt
Tide Water Associated Oil Company
Treasurer - - - - - - - - - Marjorie Fuqua
Humble Oil and Refining Company

Regular meeting held the second and fourth Mondays at noon (12 o'clock), Mezzanine floor, Texas State Hotel. For any particulars pertaining to the meetings write or call the secretary.

PANHANDLE GEOLOGICAL SOCIETY
AMARILLO, TEXAS

President - - - - - - - - - G. E. Hatton
Phillips Petroleum Company, Box 1761
Vice-President - - - - - - Robert F. Herron
Oil Development Company, 900 Polk St.
Secretary-Treasurer - - - - - Robert B. Totten
Sun Oil Company, Box 46

Meetings: Luncheon 1st and 3d Wednesdays of each month, 12:00 noon, Herring Hotel. Special night meetings by announcement.

TEXAS

WEST TEXAS GEOLOGICAL SOCIETY
MIDLAND, TEXAS
Box 1595

President - - - - - - - - - W. T. Schneider
Honolulu Oil Corporation, Box 1391
Vice-President - - - - - Ralph D. Chambers
Continental Oil Company, Box 431
Secretary - - - - - - - - - Jesse A. Rogers
The Texas Company, Box 1270
Treasurer - - - - - - John V. Norman, Jr.
Forest Oil Corporation, Box 1821

Meetings will be announced.

WEST VIRGINIA

APPALACHIAN GEOLOGICAL SOCIETY
CHARLESTON, WEST VIRGINIA
P.O. Box 2605

President - - - - - - - - - W. B. Maxwell
United Fuel Gas Company, Box 1273
Vice-President - - - - - - - John Galpin
1901 Kanawha Valley Building
Associate Vice-President - - - H. P. McJunkin
McJunkin Supply Company
Secretary-Treasurer - - - - W. T. Ziebold
Spartan Gas Company, Box 766
Editor - - - - - - F. Seigal Workman, Jr.
Acme Engineering Services, Box 923

Meetings: Second Monday, each month, except June, July and August, at 6:30 P.M., Daniel Boone Hotel.

NORTH TEXAS GEOLOGICAL SOCIETY
WICHITA FALLS, TEXAS

President - - - - - - Joseph W. McDonald
Shell Oil Company, Inc., Box 2010
Vice-President - - - - - Ralph H. McKinlay
Panhandle Producing and Refining Company
Box 1191
Secretary-Treasurer - - - - Walter L. Ammon
Stanolind Oil and Gas Company
Box 1680

Meetings: Luncheon 1st and 3d Thursdays of each month, 12:00 noon, Texas Room, Holt Hotel. Evening meetings by special announcement. Visiting geologists and friends are cordially invited to all meetings.

SOUTH TEXAS GEOLOGICAL SOCIETY
SAN ANTONIO, TEXAS

President - - - - - - - - - Paul B. Hinyard
Shell Oil Company
2000 Alamo National Building
Vice-President - - - - - - - - - J. Boyd Best
Ohio Oil Company
Secretary-Treasurer - - - Louis H. Haring, Jr.
Stanolind Oil and Gas Company

Meetings: One regular meeting each month in San Antonio. Luncheon every Monday noon at Milam Cafeteria, San Antonio.

UTAH

UTAH GEOLOGICAL SOCIETY
SALT LAKE CITY, UTAH
P.O. Box 1015

President - - - - - - - - J. Stewart Williams
Utah State Agricultural College, Logan
Vice-President - - - - - - A. Lee Christensen
Utah Construction Company, Salt Lake City
Corresponding Secretary - - - - Reed F. Welch
American Smelting and Refining Co., Salt Lake City
Recording Secretary - - - - - - Max Erickson
University of Utah, Salt Lake City
Treasurer - - - - - - - - F. W. Christiansen
University of Utah, Salt Lake City

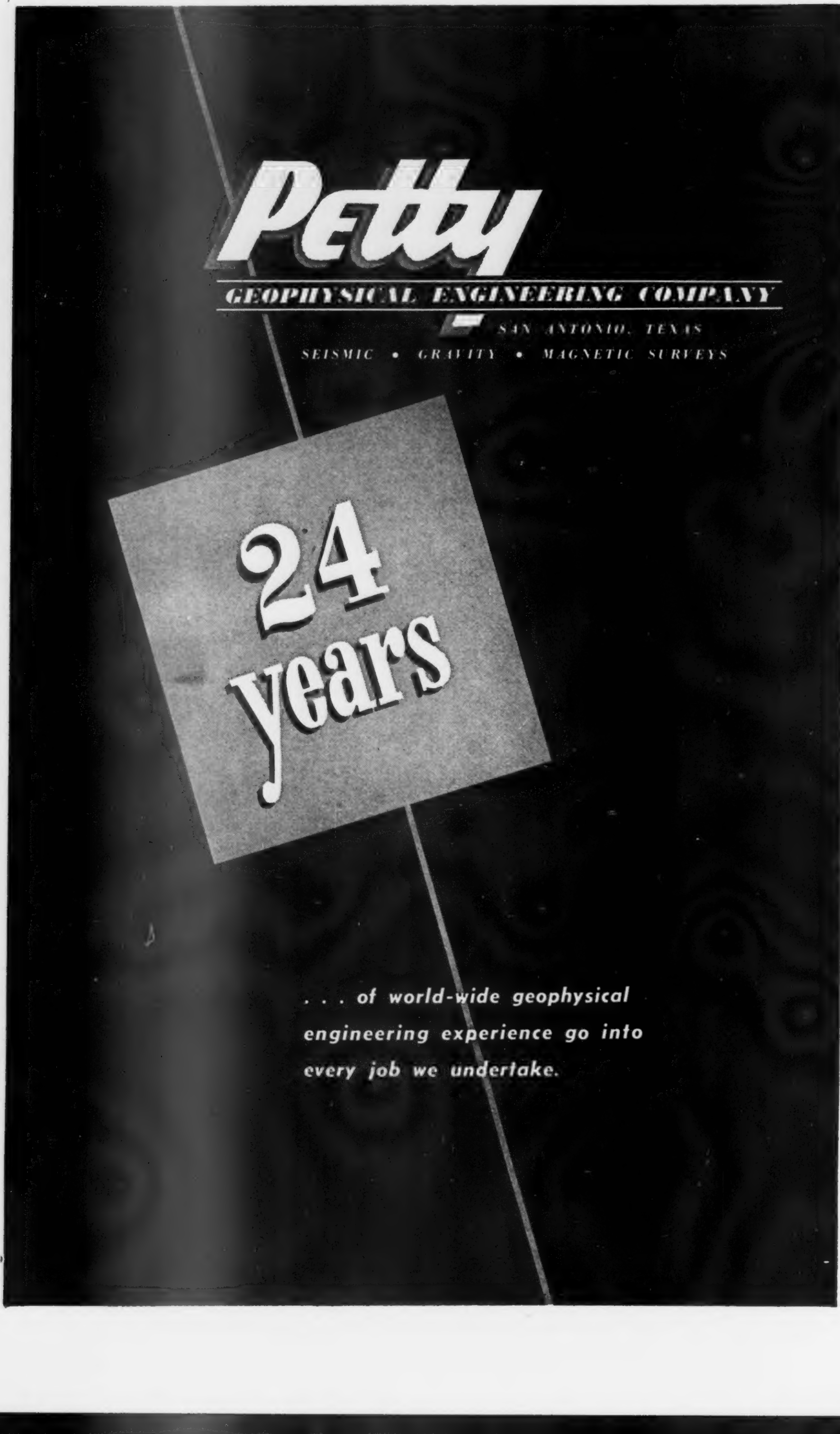
Sponsors an annual field trip for which a guidebook is published.
Meetings by announcement.

WYOMING

WYOMING GEOLOGICAL ASSOCIATION
CASPER, WYOMING
P.O. Box 545

President - - - - - - - - - Jed B. Maebius
Gulf Oil Corporation, Box 1971
1st Vice-President - - - - Emmett E. Schieck
Morton Oil Company, Box 1970
2d Vice-President (Programs) - Donald E. Edstrom
British-American Oil Producing Company, Box 620
Secretary - - - - - - - J. B. Headley, Jr.
Atlantic Refining Company
Treasurer - - - - - - - - - George L. Goodin
Petroleum Information, Inc.

Informal luncheon meetings every Friday, 12 noon, Townsend Hotel. Visiting geologists welcome. Special meetings by announcement.



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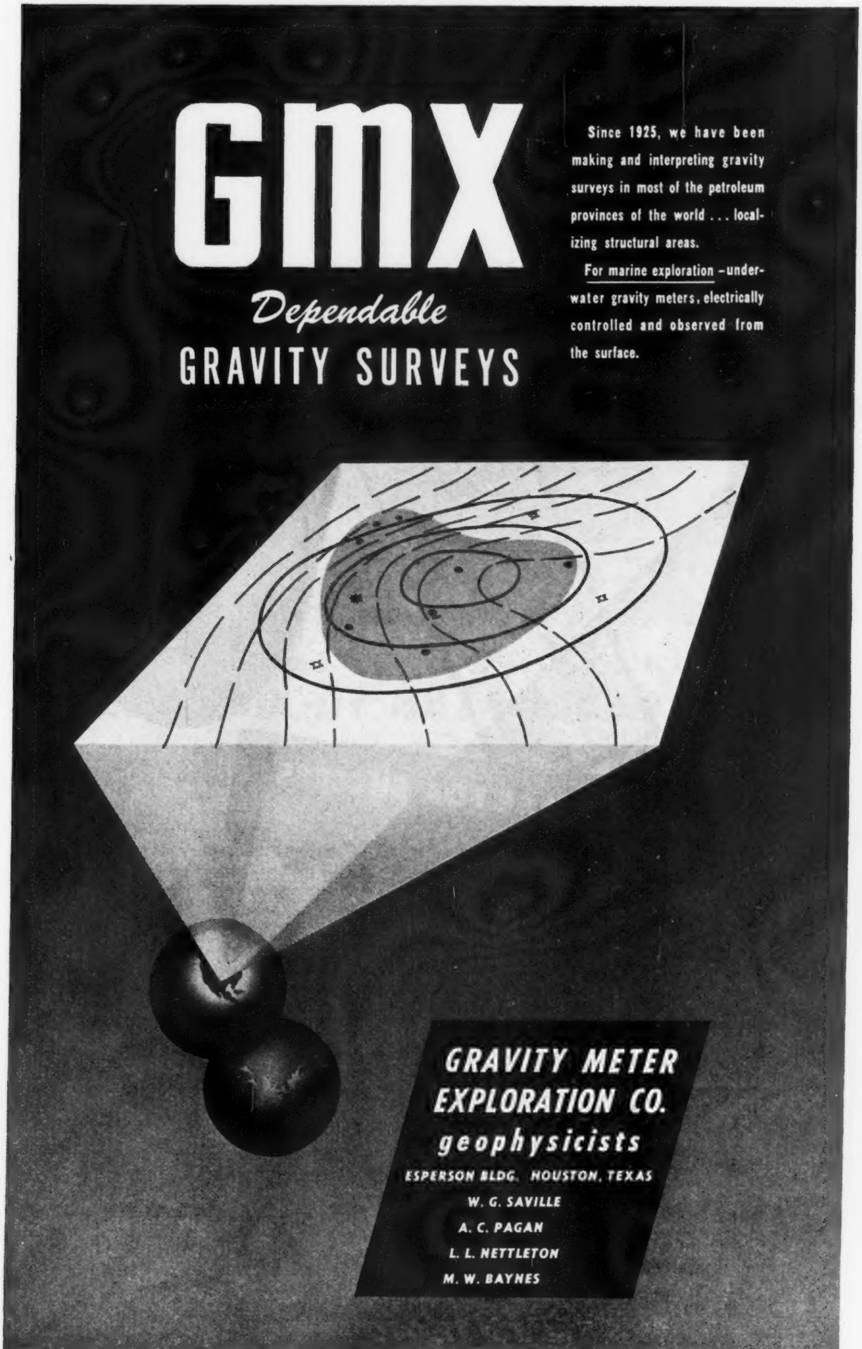
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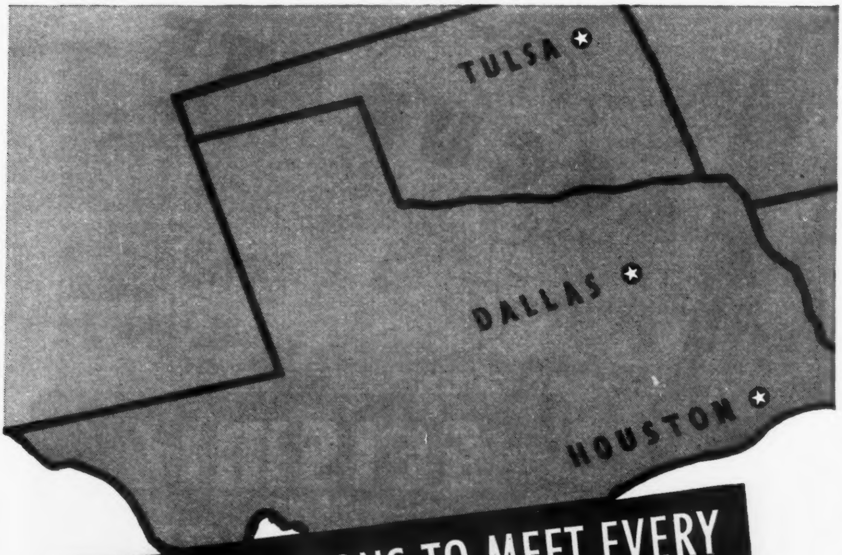
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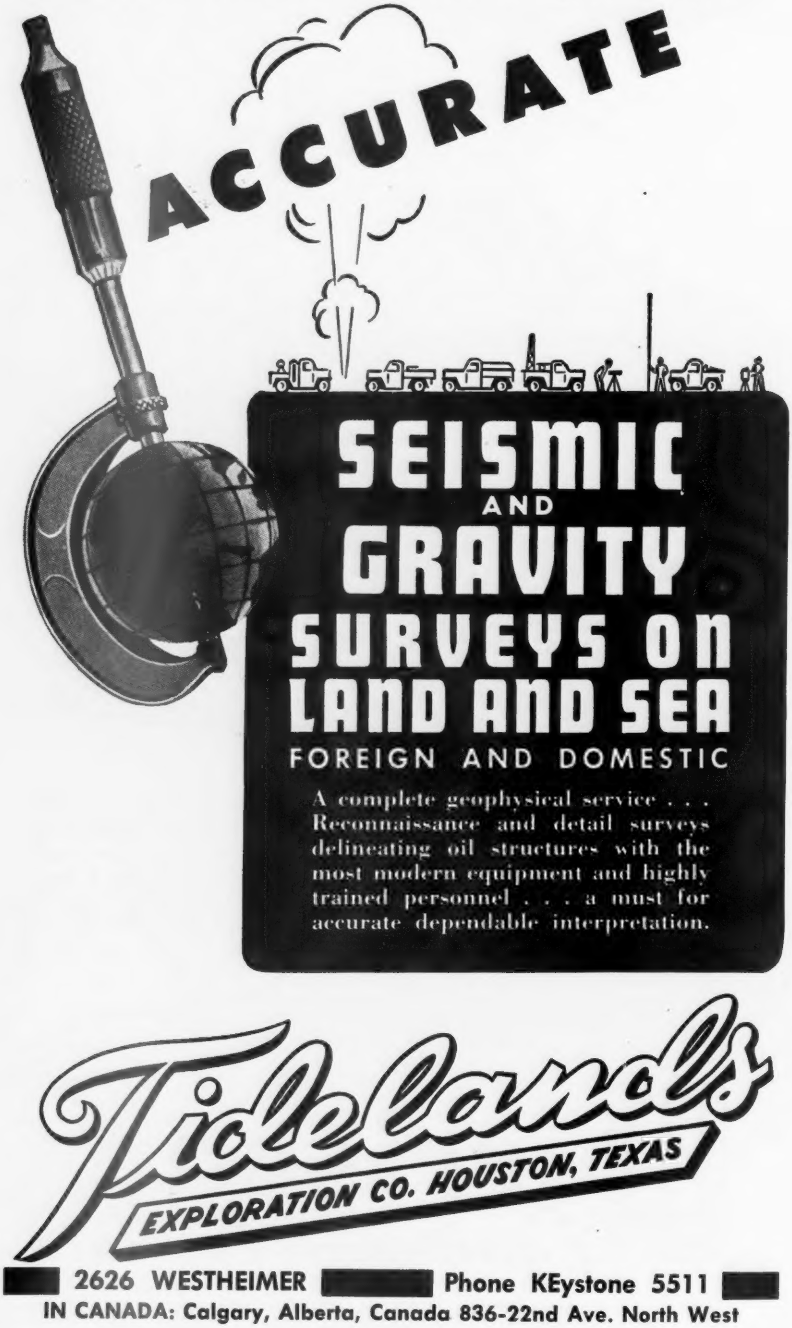
DALLAS
HOUSTON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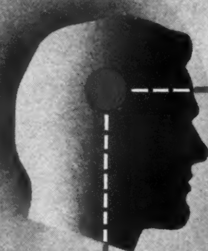

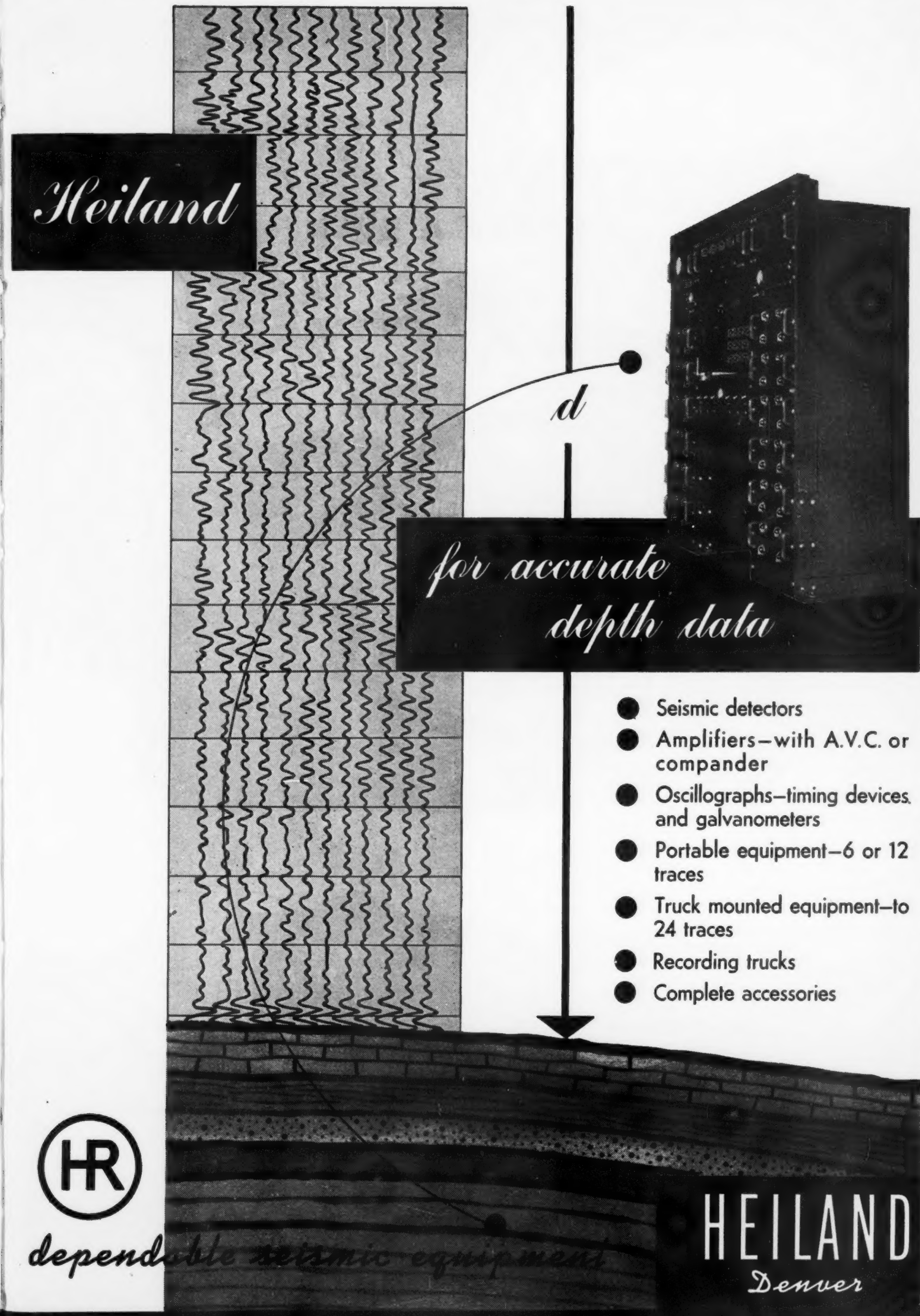
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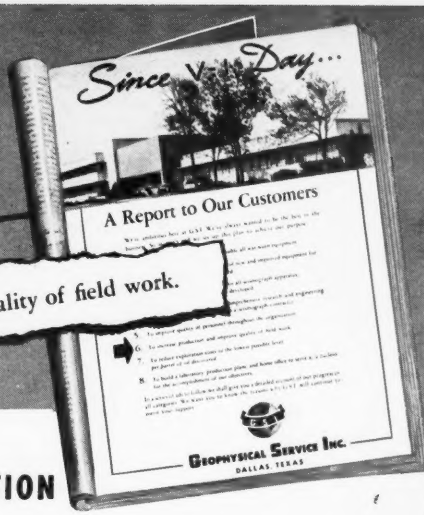
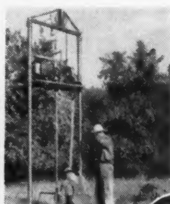


6. To increase production and improve quality of field work.

G.S.I. HAS INCREASED PRODUCTION WITH IMPROVED QUALITY BY . . .

- ***Selection of the Right Equipment for the Job—***


Heavy Drill

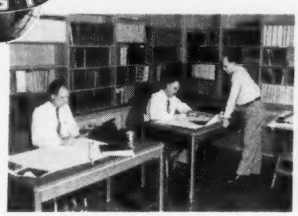

Portable Drill


Truck Recorder


Portable System


Field Check


Field Office


Technique Development


Field Supervision

- ***Operated by Competent Production Conscious Personnel . . .*** Supervisors—average 15 years experience, all college trained . . . Party Chiefs—average 8 years experience, 93% college trained . . . Field Office Employees—average 2 years experience, 93% college trained . . . All other field employees—average 4 years experience, 33% college trained.
- ***In an Efficient Manner . . .*** An expanded field engineering department recommends efficient operating and maintenance techniques on all equipment, vehicles, and procedures.
- ***Producing Quality Records Which Are Interpreted by Advanced Techniques . . .*** Skilled seismologists and mathematicians continually seek better interpretation techniques.
- ***The Entire Operation Checked Carefully by an Adequate Field Supervising Force . . .*** A current ratio of 2:1 is maintained between over-all field supervisors and number of field crews.

GEOPHYSICAL SERVICE INC.
DALLAS, TEXAS